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A Comparison of Seed- and Seedling-Focused Ecologically Based Weed Management Strategies

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A COMPARISON OF SEED- AND SEEDLING-FOCUSED ECOLOGICALLY BASED WEED MANAGEMENT STRATEGIES

By

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An Abstract of the Dissertation Presented

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Many farmers target weeds at the seedling stage, aiming to control weeds with the minimum amount of labor necessary to avoid crop yield loss. Other farmers with a more long-term, seed-focused approach aim to prevent weeds from setting seed so that emergence will be decreased in subsequent crops. These strategies likely vary in short- and long-term effects on farm ecological and economic health. In 2014–2016, I compared these strategies in a test crop of onion. Unexpectedly, due to high yields, the more labor intensive, seed-focused strategy was the most profitable. Case-study interviews of farmers who have adopted each approach indicated seed-focused management improves over time, whereas seedling-focused management becomes more challenging. A key obstacle for both seed- and seedling-focused management was the control of weeds directly in the crop row, where mechanical cultivation tools are only marginally effective due to the need to avoid crop damage. In 2015–2016, I

tested the hypothesis that rather than using just one tool, “stacking” on a second or third type of tool would increase efficacy. Indeed, for most tool combinations tested, efficacy increased in an additive manner when more tools were used. One particular combination of three tools exhibited a synergistic increase in efficacy, even over a range of conditions, suggesting that farmers could improve intra-row weed control by adopting this technology. Weed seedling control could be further improved by decreasing the burden on cultivation through a more diverse set of ecologically based weed management practices. Such tactics could be benefited by improved knowledge of the timing of weed seed germination and emergence. In 2014, I recorded the timing of emergence of weed species at Rogers Farm in Old Town, ME and found that many weed species had peak emergence periods that could be targeted by ecologically based management tactics. Overall, my research results provide farmers several ways to enhance effectiveness of ecologically based weed management by encouraging more thoughtful selection of preventative, suppressive, and reactive tactics, increased efficacy of weed seedling control, and improved timing of management activities.

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CHAPTER 1

A SYSTEMS COMPARISON OF CONTRASTING ORGANIC WEED MANAGEMENT STRATEGIES

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Chapter Abstract

Many farmers manage weed seedlings only during the early, weed-sensitive “critical period” of their crops. However, this approach often promotes late-season weed growth and abundant weed seed rain. Alternatively, some farmers perform frequent weed control events to ensure “zero seed rain,” so that weed emergence will lessen in subsequent years. Another approach is to use mulch to suppress weeds. Polyethylene (PE) mulch may be used to cover beds while paths are left bare or covered with natural mulches. Natural mulches, such as straw or hay, may also be used in the beds and paths. Each of these weed management strategies may vary in their ability to manage weeds, and likely have unique agroecological implications. To evaluate potential tradeoffs, we implemented each strategy in organically managed yellow onion. As expected, end-of-season weed biomass and weed seed production were greatest in the Critical Period system and nearly zero for the Zero Seed Rain system. Weeds were also well-controlled in natural mulch systems. Average onion yield per treatment was 50.7 Mg ha^{-1}. In one year of two, the Critical Period system and the PE mulch system demonstrated yield loss, likely due to weed competition and excessive soil temperature, respectively. Carabid beetles, earthworms, soil compaction, soil nitrate (NO_3-N), and active carbon were affected by weed management system, with natural-mulched systems generally performing most favorably. However, these benefits were not substantial enough to affect yield of a subsequent crop grown in weed-free

conditions. Contrastingly, a subsequent crop in which weeds were managed with only several cultivations, demonstrated yield loss in plots where the Critical Period system was implemented the prior year, indicating that weed competition resulting from abundant weed seed production in that system was the most influential legacy effect of the weed management strategies.

Introduction

Many farmers focus on early-season control of weed seedlings (Jabbour et al. 2014b). However, this weed management strategy may worsen weed problems over time if weeds are allowed to set seed. Conversely, farmers with a longer term, weed-seedbank-focus, attempt to prevent weeds from setting seed (Jabbour et al. 2014b). A third set of farmers avoid the need for direct weed control through use of mulch. While there are examples of successful farmers that emphasize each of these approaches (Brown and Gallandt, in review), each strategy likely has distinct agroecological implications.

Growers focusing on management of weed seedlings often prioritize control events during the crop's "critical period," when crops are most sensitive to competition and weed-free conditions should be maintained to avoid yield losses (Nieto et al. 1968). Such an approach has been used to maximize efficiency of in-season weed management (Knezevic et al. 2002), which can reduce weeding labor costs on organic farms. However, if weeds are only controlled in the early-season, later emerging weeds often set seed prior to autumn tillage. Considering that seed rain can increase the weed seedbank fifteen-fold in a single year (Bond et al. 1998), critical period weed control may perpetuate the weed problem, often necessitating an increased control effort over time.

An alternative to seedling-focused weed weed management involves a longer-term, seedbank-focused perspective. Since many weed species have seed longevity "half-lives" of less than one year (Roberts and Feast 1972), preventing seed rain causes a rapid decrease in the weed seedbank, and therefore, subsequent weed emergence, providing a labor savings in succeeding years (Norris 1999). A zero seed rain approach often utilizes frequent soil disturbance to minimize credits to the weed seedbank while maximizing debits (Forcella 2003; Gallandt 2014).

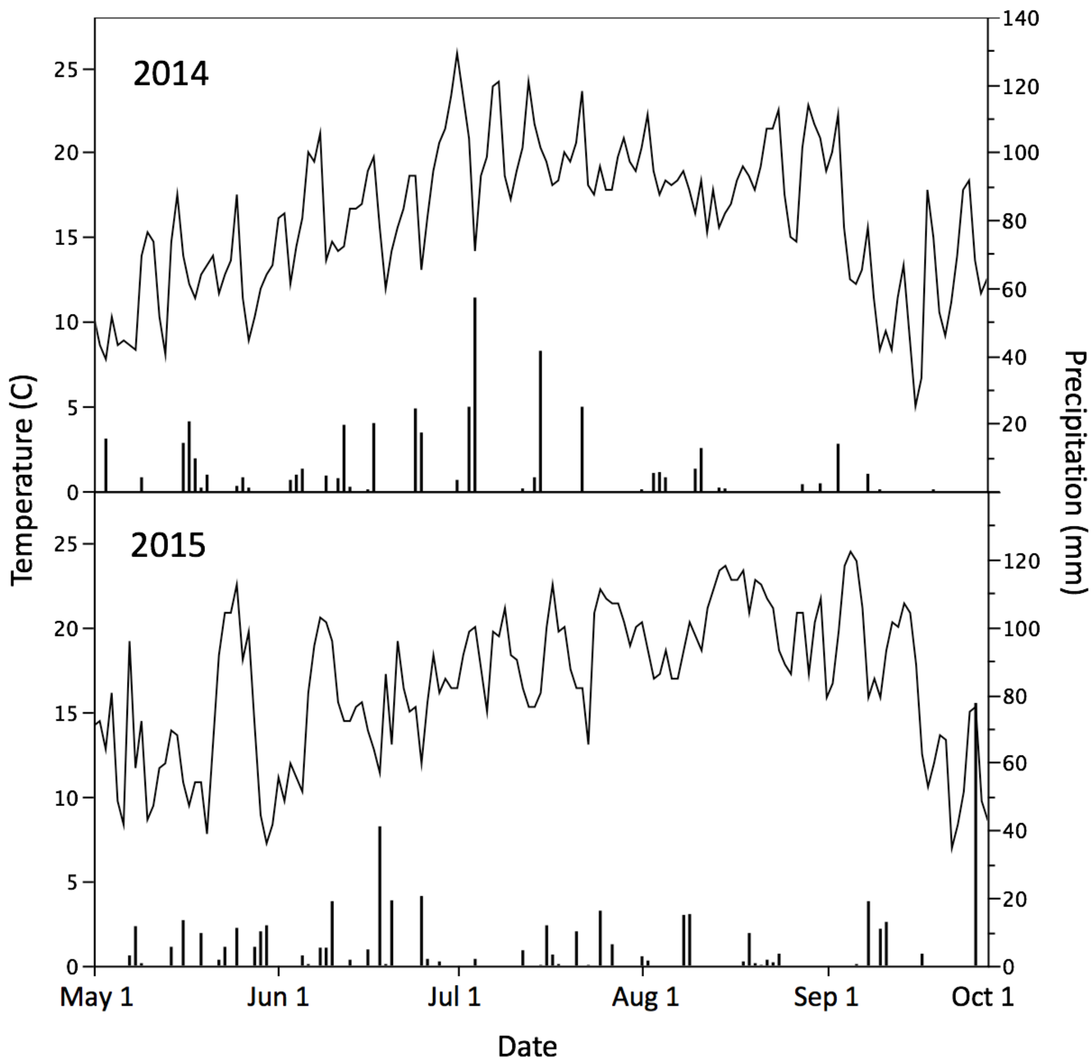
Other growers substitute direct physical weed control for weed prevention or suppression by mulch. Black PE mulch is most common, due to its ability to warm the soil and promote early yield of crops like tomatoes (Schonbeck and Evanylo 1998a). PE mulch can reduce the amount of required irrigation (Abu-Awwad 1999) and conserve soil nitrate (Schonbeck and Evanylo 1998b). On the other hand, natural mulches, such as straw or hay, may also be used to suppress weed growth (Teasdale and Mohler 2000) and improve water infiltration (Shock et al. 1999; Tindall et al. 1991), increase earthworm populations, and replace seasonal carbon and nitrogen losses (Schonbeck and Evanylo 1998b). Mulches may also reduce insect pest populations (Larentzaki et al. 2008; Van Toor et al. 2004) and disease incidence (Hill et al. 1982).

While each of these alternative weed management strategies may provide adequate crop yields, they include tradeoffs in effects on farm ecology. Grower decision of which strategy to implement should include consideration of weed management and crop yield, but also the effects on the weed seedbank, edaphic arthropods and microbes, and the relative mix of soil aggrading vs. degrading practices employed. Our aim with this project was to characterize the multiple dimensions of these fundamentally different weed management strategies in order to provide growers with improved understanding of which strategy best matches their farm management goals. Economic performance of the systems (B Brown, unpublished data) as well as a related case study narrative (Brown and Gallandt, in review) are presented elsewhere.

Materials and Methods

Field experiments comparing several contrasting weed management strategies were conducted at the University of Maine Rogers Farm in Old Town, ME (44.93°N, 68.70°W) in 2014 and 2015 on separate fields, both Nicholville very fine sandy loam. Yellow storage onions (cv. 'Cortland') were used as the test crop since they are commonly grown using each strategy. Weather conditions during the study were typical for the region (data from www.ncdc.noaa.gov). Average temperature was 16.9 and 17.2 C and total precipitation was 380 and 473 mm, for the growing periods of 2014 and 2015, respectively (Figure 1).

Figure 1.1. Average daily temperature (line) and total daily precipitation (bars) in Old Town, ME for the study periods in 2014 and 2015.



Our broad aim was to compare seedling-, seed-, and mulch-based weed management approaches. Ultimately, we chose six systems, described in detail below. Literature review and extensive interviews with farmers that have specialized in each weed management strategy (Brown and Gallandt, in review) were used to ensure that each system was implemented in a realistic manner.

Critical Period Weed Control

Weeding events were performed about every 2 wk for the duration of the critical period (Table 1.1.). The critical period for direct-seeded onions is the first 8 to 12 wk following emergence (Brewster 2008; Menges and Tamez 1981; Wicks et al. 1973). Since the onions were transplanted, we used an 8 wk critical period in 2014. However, yield loss in 2014 indicated the period was not long enough. In 2015, the critical period duration was adjusted as described by Knezevic et al. (2002), which extended it from 56 d in 2014 to 78 d in 2015.

Table 1.1. Schedule of field operations for six organic weed management strategies tested in Old Town, ME, in 2014 and 2015.

Year	Weed management system	Date				
		Planting	Mulching	Weeding	Harvest	Onion curing
2014	Critical Period	May 13	–	May 29, Jun 9, Jun 19, Jun 27, Jul 3	Sep 18	Aug 24-Oct 20
	Zero Seed Rain	May 13	–	May 29, Jun 9, Jun 19, Jun 27, Jul 3, Jul 10, Jul 30, Aug 12, Aug 26	Sep 10	Sep 13-Sep 27
	Polyethylene Mulch	May 13	May 12	Beds (Jun 9, Jun 19, Jul 10), Paths (May 29, Jun 9, Jun 19, Jun 27, Jul 10)	Aug 27	Aug 29-Sep 12
	Polyethylene Mulch, Straw Paths	May 13	May 12	Jun 9, Jun 19, Jul 10	Aug 27	Aug 29-Sep 12
	Straw Mulch	May 13	Jun 24-Jul 1	May 29, Jun 9, Jun 19, Jun 24, Jul 30	Sep 18	Aug 24-Oct 20
	Hay Mulch	May 13	Jun 24-Jul 1	May 29, Jun 9, Jun 19, Jun 24, Jul 30	Sep 18	Aug 24-Oct 20
2015	Critical Period	May 18	–	Jun 4, Jun 17, Jun 30, Jul 14, Jul 30	Sep 28	Sep 29-Oct 26
	Zero Seed Rain	May 18	–	Jun 4, Jun 17, Jun 30, Jul 14, Jul 30, Aug 11, Aug 20, Sep 10	Sep 28	Sep 29-Oct 26
	Polyethylene Mulch	May 18	May 14	Beds (Jun 22, Jul 14, Aug 11), Paths (Jun 17, Jun 30, Jul 14, Jul 30, Aug 14)	Sep 10	Sep 12-Sep 29
	Polyethylene Mulch, Straw Paths	May 18	May 14	Jun 17, Jul 14, Aug 11	Sep 10	Sep 12-Sep 29
	Straw Mulch	May 18	Jul 2	Jun 4, Jun 17, Jun 30, Aug 11	Sep 28	Sep 29-Oct 26
	Hay Mulch	May 18	Jul 2	Jun 4, Jun 17, Jun 30, Aug 12	Sep 28	Sep 29-Oct 26

Zero Seed Rain

For this system, beds and paths were weeded about every 2 wk throughout the growing period (Table 1.1.) with a goal of completely preventing weed seed inputs to the seedbank.

Polyethylene (PE) Mulch

Embossed black PE mulch 1.2 m wide, 0.025 mm thick (FedCo Seeds, Waterwille, ME) was applied with a mechanical applicator (Model 385PL, Bartville Welding Shop, Christiana, PA) prior to transplanting. Transplanting holes were made with a 5 cm wide trowel. Weeds in planting holes were hand-pulled several times, while paths were cultivated more frequently (Table 1.1.).

PE Mulch with Straw Mulched Paths

Mulch was applied and beds were weeded in the same manner as above. Before planting, oat (*Avena sativa* L.) straw was applied to the paths at a rate of 20 Mg ha^{-1} (Schonbeck 1998). Weeds and volunteer oat emerging through the straw required hand-pulling (Table 1.1.).

Straw Mulch

Oat straw was applied more than one month after transplanting (Table 1.1.) to allow time for the soil to warm and for onions to grow large enough to withstand the disturbance of mulching. Straw was applied by hand at a rate of 20 Mg ha^{-1} (Schonbeck 1998). Straw was spread quickly in the paths, but in the beds it was carefully laid in bundles around the onions. One hand-pulling event was necessary to control weeds and volunteer oat after the mulch was applied.

Hay Mulch

Decaying timothy (*Phleum pratense* L.) hay, not suitable for horses, was obtained locally. Hay was applied and managed in the same manner as the Straw Mulch (Table 1.1.).

Experimental Design

Each of the six weed management systems was implemented as a treatment in a randomized complete block design with four replicates. Each plot was 6.1 m long by 1.7 m wide. To ensure consistent competition and edge effects, a buffer bed of onions was transplanted on either side of each plot and blocks were separated by an unplanted area of 2.4 m.

Primary and secondary tillage were conducted using a rototiller and field cultivator, respectively. Pre-planting fertility was applied based on soil test recommendations prior to secondary tillage. In 2014, 1,483 kg ha^{-1} soybean meal (7.0-0.5-2.3, FedCo Seeds, Waterville, ME), 908 kg ha^{-1} composted poultry litter (3-2-3, MicroStart 60, Perdue Agribusiness LLC, Salisbury, MD), 454 kg ha^{-1} bone char (0-16-0, FedCo Seeds, Waterville, ME) provided 131-98-61 kg ha^{-1} (N-P-K). In 2015, 1,337 kg ha^{-1} soybean meal, 1,110 kg ha^{-1} dehydrated poultry litter, and 441 kg ha^{-1} bone char provided 127-100-64 kg ha^{-1} (N-P-K). All materials were measured and applied by hand.

Onions were started in late February in a heated greenhouse. Flats containing an organic potting mix (Light Mix, Living Acres, Inc., New Sharon, ME) were planted with 500 seeds per flat. In the period prior to transplanting, seedlings were fertilized three times with fish hydrolysate (2.9-3.5-0.3, FedCo Seeds, Waterville, ME) diluted to 1% concentration. Transplanting was done by hand in May (Table 1.1.), following tillage and PE mulch application. To reduce transplant shock, onion tops were trimmed to 13 cm the day prior to planting. Onions were bare-root transplanted with roots trimmed to 3 cm. Transplanting was done by block. Each plot contained one bed of three onion rows, with rows spaced 30 cm apart, planting holes 15 cm apart, and two onions per hole. An additional 408 kg ha^{-1} fish hydrolysate was applied immediately following transplanting.

Paths were weeded with wheel hoes, long-handled hoes were used closer to crop rows, short-handled hoes were used in the crop row, and hand-pulling was only necessary for mulched plots. Buffer beds were unmulched and weeded every 2 wk throughout the season. Weed-free subplots 2.0 m long by 1.7 m wide were established within each main plot and were weeded at least weekly to ensure that weed competition did not affect yield.

Optimal soil moisture was maintained for each system using drip irrigation (Triple K Irrigation, Morenci, MI) with 16 mm diameter emitters spaced every 30 cm that each output 19 cc min^{-1}. Irrigation was setup prior to transplanting, with one line per bed. Soil water holding capacity was determined by examining soil moisture over time after a heavy rain. Capacity was estimated to be 17 and 20% volumetric soil moisture for 2014 and 2015 fields, respectively. Volumetric soil moisture was measured weekly with a Delta-T HH2 Soil Moisture Meter with a 5.1 cm Theta Probe (Delta-T Devices, Burwell, UK) at four locations in each plot to determine the amount of irrigation needed to recharge the water deficit to a depth of 32 cm.

Data Collection

End-of-season aboveground weed biomass was measured within 1 d of harvest using a 0.25 m^2 quadrat placed randomly in the bed and randomly in the paths of each plot. Within the quadrat, all weeds were clipped at the soil surface, and separated by species. Samples were placed in drying ovens for 1 wk at 46 C, and dried samples were weighed. Weed seeds were threshed from the dried weed samples and weighed. The total number of weed seeds was found by dividing the total seed mass of each species by the average mass of a single seed. To evaluate the amount of weed seed in the organic mulches, in July of each year, four 100 g samples of each mulch were laid on flats of sterile potting mix (ProMix All Purpose Mix, Premier Tech, Quebec, Canada) and covered with a 1 cm layer of potting mix. Flats were watered regularly for one month to encourage germination. Emerged seedlings were identified, recorded, and removed.

Early season onion leaf length was determined based on the average length of the longest leaf of four randomly chosen onions per plot on June 27, 2014 and July 9, 2015.

Onions were harvested at 70% “tops-down” on a per treatment basis. Harvest occurred in a 1 m by 1 m quadrat centered on the bed in a random location within each main plot and each weed-free subplot. Harvested onions were laid in a single layer on wire tables in a ventilated greenhouse to cure.

Treatments harvested later in the season required a longer curing duration (Table 1.1.), likely due to decreased temperature and decreased light intensity. Once all onion tops had dried to a brown papery state, roots and loose scales were removed, tops were cut 1-cm above the folding point in the neck, and onion bulbs were weighed. Visibly diseased onions were not included in yield data. Diseases were diagnosed by plant pathologist Dr. Jianjun Hao.

In December of each year, following an autumn cooling period in an unheated barn, four marketable onions from each plot were randomly selected to be stored in a walk-in cooler at 1.7 C and 75% relative humidity. The 2014 and 2015 onions were removed from cold storage May 19, 2015 and July 15, 2016, respectively. Firmness was tested using a Brookfield LFRA Texture Analyzer (Brookfield Ametek, Inc., Middleboro, MA) running at 4 mm sec^{-1} with a 5 cm diameter acrylic compression head. When the head confronted an 8 g trigger it measured peak pressure required to continue for 1.5 mm. Onion pH and soluble solids were measured using an Orion Star A211 pH Meter (Thermo Fisher Scientific, Waltham, MA) and an Atago rx-5000i Refractometer (Atago U.S.A., Inc., Bellevue, WA), respectively, using blended samples from each plot.

Throughout the field experiments, soil temperature was measured at a depth of 5 cm, once per week in the mid-afternoon using an Omega Model HH21 Microprocessor Thermometer with a Hanna Type K Thermocouple (Omega Engineering, Inc., Stamford, CT).

Activity-density of granivorous carabid beetles including genera *Amara*, *Bembidion*, *Clivinia*, *Harpalus*, *Poecilus*, and *Pterostichu*s, was measured in early August by installing one pitfall trap in a random location in the bed of each plot using methods adapted from Birthisel et al. (2014). A 30 cm slit was cut in the PE mulch treatments to facilitate installation. Traps were examined four times in 2014 and twice in 2015, with 24 h to 48 h catch time for each event. Earthworm abundance was measured by excavating a 15 cm by 42 cm by 20 cm volume between onion rows in each plot in late August, and sifting samples following Edwards and Lofty (1977).

Onion thrips (*Thrips tabaci* Lind.) populations were measured weekly in 2014 using a hand lens to count the thrips on eight random onion plants per plot. In 2015, the destructive sampling method of Larentzaki et al. (2008) was adopted. The revised method was implemented once in June, July, and August. An action threshold of 3 thrips per leaf was not attained in either year. Additionally, in 2015, plots were examined for other arthropod and disease damage by four field scouting events in August.

In late August of each year, several soil quality measurements were conducted. Soil samples collected to a depth of 15 cm from ten random locations within the bed of each plot were analyzed for nitrate (NO_3-N), ammonium (NH_4-N), and active carbon, which includes an estimate of microbial biomass. In addition, soil water infiltration rate was measured by recording the time required for 1 L water to soak into pre-wet soil inside a 20 cm diameter aluminum cylinder that had been inserted 8 cm into the soil (Anderson and Ingram 1989). Compaction was measured at four locations per plot using a penetrometer with 1 cm tip that was inserted to a resistance of 2.1 Mpa – enough compaction to severely impair root growth (Bengough and Young 1993).

Legacy Effects of Treatment

In September 2014 and 2015, immediately following onion crop harvest, fields were rototilled and oats (cv. 'Aroostook') were planted with a 3 m grain drill (Massey Ferguson, Duluth, GA) with 15 cm row spacing at a rate of 224 kg ha^{-1}. In May 2015 and 2016, prior to incorporating the oats, soil organic matter was tested from a homogenized sample of ten soil cores per plot, to a depth of 15 cm. In 2015, analyses were conducted with a 2 mm, but in 2016, a 5 mm sieve was used so that more of the residue would be included in the test. Since organic matter may have exceeded 2 mm, this test included raw residue. Samples were also combusted using 20 to 25 g rather than 4 to 5 g amounts. Immediately following soil sampling, oats were incorporated by rototilling and field cultivating.

In 2015 only, sweet corn (cv. Xtra-Tender 3473) was planted on June 4 with rows spaced 81 cm apart and plants 20 cm apart within rows. In this spacing, two rows were centered within the bounds of the previous year's plots. Most fertility (1,318 kg ha^{-1} soybean meal, 412 kg ha^{-1} composted poultry litter, and 165 kg ha^{-1} bone char) was applied prior to secondary tillage and additional fertility (659 kg ha^{-1} composted poultry litter and 329 kg ha^{-1} fish hydrolysate) was sidedressed on July 10, providing a total of 134-66-63 kg ha^{-1} (N-P-K). To protect the corn from crows, plots were covered with spun-bonded polypropylene (Agribon, San Luis Potosi, Mexico) until the corn was in the three-leaf stage. The corn was managed uniformly across all previous treatments. Weed control consisted of a spring tine harrowing (Lely Industries NV, Series 982, Type 3, Maasland, Holland) on June 15; inter-row cultivations with a 4-row Case International Model 183 (Case IH, Racine, WI) with Danish S-tines and 10 cm sweeps and gage wheels on June 15, June 25, and July 7; and disc hillings (Weedmaster, Elomestari Oy, Ltd., Kukkola, Finland) on June 25 and July 10. In addition to the field-wide cultivations, weed-free subplots were maintained by hand-weeding on June 19, July 6, July 20, July 31, and August 12. Harvest of first ears occurred on August 24 and second ears on September 2. Entire plots were harvested for yield data. Yield was defined as the fresh mass of ears from both harvests. Corn earworm (*Helicoverpa zea* Boddie) damage was evaluated in ten ears per plot on the second harvest date.

Statistical Analyses

All analyses were completed using JMP 10 (SAS Institute Inc., Cary, NC). Analysis of variance (ANOVA) was used to determine effects of weed management system on dependent variables. Due to several important Year*Treatment interactions, years were analyzed separately. Fisher's Protected LSD was used for means comparisons unless otherwise stated. An alpha level of 0.05 was used throughout. Data failing to meet assumptions for ANOVA were subjected to log, square root, or Box-Cox (Box and Cox 1964) transformations as necessary. Data unable to pass assumptions after transformations were analyzed with the nonparametric Kruskal Wallis test (Kruskal and Wallis 1952). Pairwise Wilcoxon signed-rank tests (Wilcoxon 1945) were used for means comparisons as appropriate. If an effect of weed management system was present in onion yield of weed-free subplots, edaphic variables that were affected by system were evaluated as main effects in a linear regression model of onion yield. Stepwise backward selection was used to eliminate non-significant variables, followed by evaluation with adjusted R^2 and Akaike Information Criterion with correction for finite sample sizes (Akaike 1974). To evaluate the effects of each system on subsequent crops, an orthogonal contrast was used to distinguish between sweet corn yield of the Critical Period system versus all others.

Results and Discussion

In-season Effects of Weed Management System

The six weed management strategies in this experiment varied in their effects on weed biomass and seed production, onion yield and storability, soil health, and edaphic invertebrates.

The most abundant weed species included were common lambsquarters (*Chenopodium album* L.), smooth crabgrass (*Digitaria ischaemum* Schreb.), and low cudweed (*Gnaphalium uliginosum* L.). As expected, in both years, the Critical Period system had the greatest weed biomass (Table 1.2.), reflecting uncontrolled weed growth in late July, August, and early September. The reduction in weed biomass in 2015 compared to 2014 was expected because we extended the critical period in that year. Weed biomass was least in Zero Seed Rain, Straw Mulch, and Hay Mulch treatments, commensurate with the increased labor required for those systems (B Brown, unpublished data). Comparatively, PE mulched plots had greater weed biomass, likely due to the infrequent weeding events that were advised by farmers, as well as the difficulty controlling weeds emerging from the planting holes and the margins of the PE mulch.

As expected, weed seed production was greatest for the Critical Period treatment and close to zero in the Zero Seed Rain system (Table 1.2.). Weed seed production in PE mulched treatments was greater than that of Zero Seed Rain, but production in natural-mulched treatments was not (Table 1.2.). Average weed seed production of the Critical Period systems was 25,359 seeds m^{-2}, which is surprising given that previous work with Maine organic vegetable farms found that most had germinable weed seedbanks of less than 15,000 seeds m^{-2} (Jabbour et al. 2014b).

Table 1.2. Effects of weed management system on end-of-season aboveground weed biomass and weed seed production. Data was collected immediately after onion harvest in 2014 and 2015. Within each column, means followed by the same letter are not significantly different.

Weed management system	End-of-season aboveground weed biomass[a]		Weed seed production[b]	
	2014	2015	2014	2015
	g m^{-2}		no. m^{-2}	
Critical Period	619 a	367 a	29,042 a	21,675 a
Zero Seed Rain	7 c	8 c	0 c	57 d
Polyethylene Mulch	97 b	117 b	787 b	5,277 b
Polyethylene Mulch, Straw Paths	110 b	161 ab	1,267 b	4,515 b
Straw Mulch	10 c	20 c	27 c	285 cd
Hay Mulch	15 c	16 c	19 c	599 c
ANOVA		P		
System	<0.001	<0.001	<0.001	<0.001

[a] Means separated using Fisher's Protected LSD test at P ≤ 0.05.
[b] Box-Cox transformed for ANOVA and Fisher's Protected LSD test at P ≤ 0.05. Reported values untransformed.

An unexpected result was that the oat straw mulch contained a large amount of oat seed (contributing 711 total seeds m^{-2}, mostly oats) even though it was baled after oat harvest. Oat seed was able to germinate and emerge from within the mulch, which likely affected yield, and required extra weed management. In contrast, hay mulch added 991 weed seeds m^{-2}, but had much less weed emergence through the mulch (data not shown).

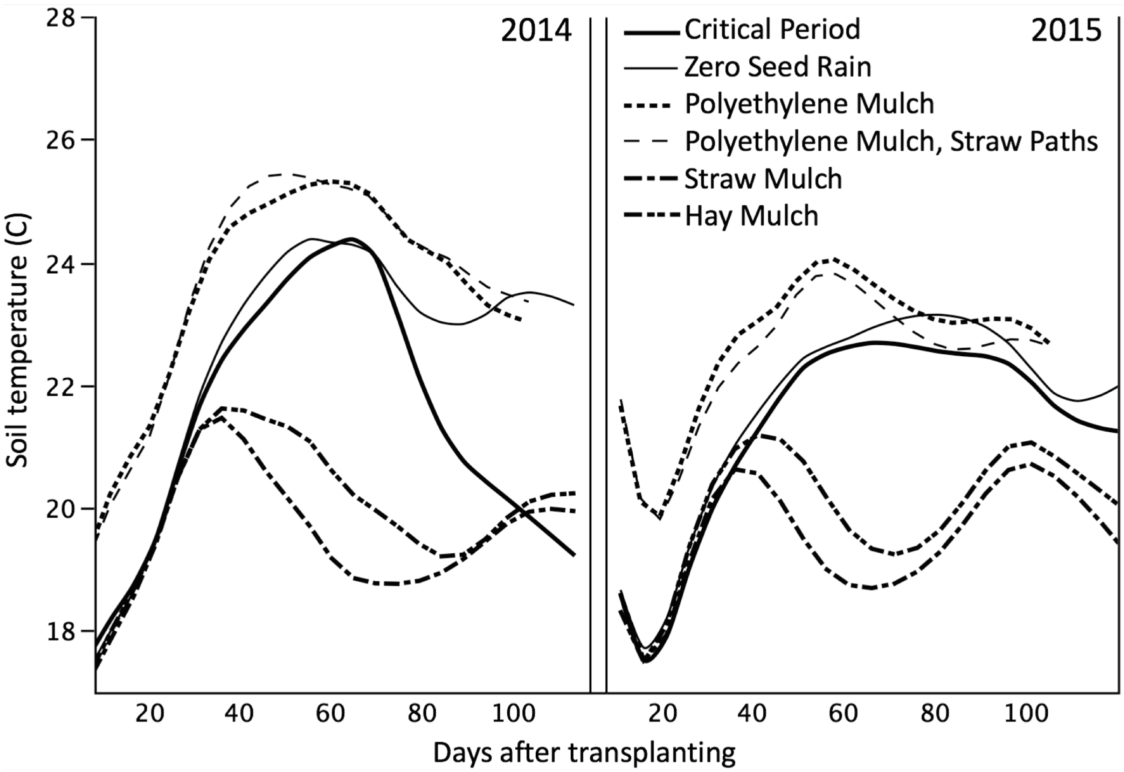
Onion yield varied by system in 2014, with Zero Seed Rain and natural-mulched systems yielding greatest (Table 1.3.). Compared to the Hay Mulch system, PE mulching and Critical Period treatments demonstrated a yield loss. Onion yield in weed-free subplots also varied by system in 2014, with PE mulched treatments yielding least, possibly due to higher soil temperatures, which accelerated early-season leaf growth (Table 3) (*in sensu* Anisuzzaman et al. 2009), and likely contributed to the onions in the PE mulched systems senescing and requiring harvest 22 d earlier than most others (Table 1.1.). However, in 2015, onion yields were similar across strategies in main plots and weed-free subplots (Table 1.3.). This result reflects the lengthened weed control period (Table 1.1.) for the Critical Period treatment and reduced soil temperatures (Figure 1.2.) that slowed maturation of the onions in the PE mulched systems, allowing more bulbing time before senescence and harvest (Table 1.1.). Similarly, in Maine, lighter colored PE mulches are beginning to be used to avoid causing premature onion senescence (J Kafka, personal communication).

Table 1.3. Effects of weed management system on early onion growth and yield in 2014 and 2015. Within each column, means followed by the same letter are not significantly different.

Weed management system	Early season leaf length[a]		Yield[a]		Weed-free yield	
	2014	2015	2014	2015	2014[b]	2015[a]
	cm		Mg ha^{-1}		Mg ha^{-1}	
Critical Period	29 b	34 bc	34.6 c	47.7	53.1 c	55.2
Zero Seed Rain	27 bc	33 c	52.5 ab	58.2	51.7 abcd	55.3
Polyethylene Mulch	35 a	43 a	42.5 bc	52.7	43.0 bcd	56.5
Polyethylene Mulch, Straw Paths	35 a	44 a	47.4 b	44.9	48.5 d	58.4
Straw Mulch	29 b	38 b	51.9 ab	46.7	64.3 a	63.2
Hay Mulch	24 c	35 bc	60.5 a	53.6	58.6 ab	52.0
ANOVA			P			
System	<0.001	<0.001	0.003	0.184	0.009	0.660

[a] Means separated using Fisher's Protected LSD test at P ≤ 0.05.
[b] Main effects tests performed with Kruskal Wallis tests and means comparisons performed with Wilcoxon paired tests, both at P ≤ 0.05.

Figure 1.2. Afternoon soil temperature measured at a depth of 5 cm for each weed management system in 2014 and 2015. Each line represents weekly afternoon soil temperature readings smoothed by a cubic spline (lambda = 0.05). Readings were discontinued after harvest of each treatment.



After harvest, onions with apparent defects were evaluated for disease. Diseases included black mold (*Aspergillus niger*), bacterial soft rot (*Dickeya chrysanthem* or *Pectobacterium carotovorum* subsp. *carotovorum*), and blue mold (*Penicillium* spp), however disease incidence was very low and not affected by weed management system.

Following cold storage, soluble solids levels, indicative of onion sugars and storability (McCallum et al. 2006), were greatest in the highest-yielding treatments of 2014 (Table 1.4.). Onion firmness, a desirable post-harvest trait (Larsen et al. 2009), was greatest in unmulched systems in 2014 (Table 1.4.).

However, these quality parameters were not affected by treatment in 2015. Onion pH, sprouting, mold, and rot were also examined but were unaffected by weed management system (data not shown).

Table 1.4. Effects of weed management system on onion bulb firmness and soluble solids after a period of cold storage. Within each column, means followed by the same letter are not significantly different.

Weed management system	Bulb firmness		Soluble Solids	
	2014[a]	2015[c]	2014[a]	2015[b]
	kg		brix	
Critical Period	3.3 ab	2.5	6.6 c	7.3
Zero Seed Rain	3.5 a	2.5	7.6 a	7.2
Polyethylene Mulch	2.6 c	2.5	6.7 c	7.4
Polyethylene Mulch, Straw Paths	2.7 c	1.9	6.9 bc	7.1
Straw Mulch	2.9 bc	2.2	7.4 ab	6.8
Hay Mulch	2.7 c	2.5	7.7 a	7.1
ANOVA	P			
System	0.011	0.614	0.008	0.948

[a] Means separated using Fisher's Protected LSD test at $P \leq 0.05$.
[b] Log transformed for ANOVA at $P \leq 0.05$. Reported values untransformed.
[c] Main effects tests performed with Kruskal Wallis tests at $P \leq 0.05$.

Soil temperature was greatest under black PE mulch (Figure 2), as expected and consistent with Hill et al. (1982). Late in the season, soil temperatures in Zero Seed Rain system approached those of PE mulched systems, likely due to the soil remaining unshaded by weeds. Conversely, soil temperature in the Critical Period system dropped as late-season weeds emerged. Soil temperature in natural-mulched plots cooled after mulch was applied, as reported elsewhere (Teasdale and Mohler 1993).

Soil moisture was maintained optimally for each system by drip irrigation. In 2014, Critical Period and Zero Seed Rain treatments received 5,600 cc water m^{-2} and PE and natural-mulched plots required 13% less irrigation. In 2015, the Zero Seed Rain system required the most irrigation (11,000 cc m^{-2}) while the Critical Period, Straw Mulch, Hay Mulch, PE Mulch, and PE Mulch with Straw Paths treatments required 11, 20, 22, 45, and 47% less water, respectively.

Activity-density of carabid beetles, including *Harpalus rufipes* Deg., a well-known seed predator (Gallandt et al. 2005), was greatest in the Critical Period system (Table 1.5.), possibly due to the habitat provided by weeds. Similarly, within crop fields, carabid activity-density (Shearin et al. 2008) and weed seed predation (Birthisel et al. 2015) have been positively correlated with vegetative cover. Earthworms were more abundant in natural-mulched systems (Table 1.5.), as found by Schonbeck and Evanylo (1998b). Earthworms are generally beneficial for increasing soil humus and aeration (Edwards and Lofty 1977; Hopp and Hopkins 1946).

Table 1.5. Effects of weed management system on beneficial invertebrates in 2014 and 2015. Measurements were conducted in August of each year. Within each column, means followed by the same letter are not significantly different.

Weed management system	Carabid activity-density[a]		Earthworms[a]	
	2014	2015	2014	2015
	no. trap^{-1}		no. m^{-2}	
Critical Period	21 a	42 a	24 b	112 bc
Zero Seed Rain	3 cd	9 c	20 b	60 c
Polyethylene Mulch	8 b	25 b	8 b	64 c
Polyethylene Mulch, Straw Paths	5 bc	17 b	24 b	52 c
Straw Mulch	2 d	4 c	104 a	164 ab
Hay Mulch	1 d	7 c	108 a	184 a
ANOVA		P		
System	<0.001	<0.001	<0.001	0.002

[a] Means separated using Fisher's Protected LSD test at $P \leq 0.05$.

Invertebrate pests and onion diseases included onion thrips (*Thrips tabaci* Lindeman), onion maggot (*Delia antiqua* Meigen), cutworm species (family Noctuidae), saltmarsh caterpillar (*Estigmene acrea* Drury), and purple blotch (*Alternaria porri* Ellis), but occurrence was highly variable and not affected by weed management system (data not shown).

End-of-season soil quality was generally most favorable for the mulched treatments (Table 1.6.). Penetrometer tests measuring soil compaction varied by system in 2014, with mulched plots demonstrating less compaction, possibly due to decreased soil crusting (Schonbeck 2012) or management-related traffic. Water infiltration rate, a measure expected to be inversely related to compaction, was not affected by system in 2014 ($F_{5,15} = 1.66$, $P = 0.206$) or 2015 ($F_{5,15} = 0.77$, $P = 0.584$). Soil nitrate (NO_3-N) was greatest in PE mulched systems in both years, a result observed elsewhere in the literature (Schonbeck and Evanylo 1998b), possibly due to increased mineralization or decreased leaching in heavy rains. Ammonium (NH_4-N) was also tested but did not differ by system in 2014 ($F_{5,15} = 0.46$, $P = 0.802$) or 2015 ($F_{5,15} = 0.77$, $P = 0.624$). Active carbon, an indicator of soil health, was greatest in Critical Period and natural-mulched treatments in 2014, likely due the reduced late-season soil disturbance to these treatments (Islam and Weil 2000). It is unclear why the PE mulched systems did not also display increased active carbon. One possible explanation is the effect of increased soil temperature on microbial biomass (Scopa and Dumontet 2007).

Table 1.6. Effects of weed management system on four measures of soil quality in 2014 and 2015. Within each column, means followed by the same letter are not significantly different.

Weed management system	Depth to compaction[a]		Nitrate (NO_3-N)[c]		Active carbon (microbial biomass)[a]		Soil organic matter[a]	
	2014	2015	2014	2015	2014	2015	2014	2015[d]
	cm		mg kg^{-1}		mg kg^{-1}		%	
Critical Period	29 bc	24	4 d	8 c	56 a	51	4.4	4.5 c
Zero Seed Rain	27 c	31	9 c	25 bc	49 b	56	4.4	4.5 c
Polyethylene Mulch	41 a	31	63 a	110 ab	47 b	37	4.4	4.5 c
Polyethylene Mulch, Straw Paths	39 a	35	121 a	114 a	48 b	42	4.6	4.7 c
Straw Mulch	37 ab	27	9 c	13 c	58 a	55	4.2	6.0 a
Hay Mulch	35 ab	34	17 b	6 c	55 a	46	4.4	5.4 b
ANOVA					P			
System	0.008	0.116	<0.001	0.004	0.006	0.166	0.405	<0.001

[a] Means separated using Fisher's Protected LSD test at $P \leq 0.05$.

[b] Log transformed for ANOVA at $P \leq 0.05$. Reported values untransformed.

[c] Box-Cox transformed for ANOVA and Fisher's Protected LSD test at $P \leq 0.05$. Reported values untransformed.

[d] Soil organic matter testing modified to include larger-sized residue.

In 2014, onion yield in weed-free conditions was affected by weed management system (Table 1.3.). To investigate which factors, other than weeds, affected yield, a linear regression model of onion yield was created with select soil-related main effects (Table 1.7.). The model was reduced to earthworm abundance and mean soil temperature. Earthworms may have positively affected yield due to their previously discussed effects on soil quality. Soil temperature was likely related to the early senescence of onions in the black PE mulched systems.

Table 1.7. The significance of soil-related parameters on the onion yield of main plots in 2014.

Soil-related parameter	Full model	Reduced model[a]
	P	
Mean soil temperature	0.231	0.139
Earthworms	0.028	0.008
Compaction	0.802	–
Soil nitrate (NO_3-N)	0.884	–
Active carbon (microbial biomass)	0.755	–
Model performance		
P	0.127	0.011
Adjusted R^2	0.179	0.290
AICc	521.9	511.2

[a] Stepwise backward elimination of least significant parameters was used to reduce the model based on the adjusted R^2 and Akaike Information Criterion with correction for finite sample sizes (Akaike 1974).

Legacy Effects

An important factor in weed management relates to how current actions will affect future management, especially for farmers with a long-term focus. Thus, effects on soil organic matter and crop yield were evaluated in the year after the weed management systems were implemented.

In May, following the initial onion crop, residue from the natural mulches was still evident despite rototilling and winter cover cropping. However, traditional soil organic matter analyses did not differ between weed management strategies (Table 1.6.). In May following the second onion crop, a revised method showed that the Straw Mulch treatment had the greatest combined soil organic matter and residue, followed by Hay Mulch, while other treatments remained at baseline levels. The difference between straw and hay mulches may relate to the higher carbon:nitrogen ratio of straw (Schonbeck 2012), since equal masses were applied.

Despite visible differences in residue and accompanying differences in other soil properties, yield of sweet corn in weed-free subplots did not differ by system in the year following onions, nor did earworm damage (data not shown). This indicates that a single year of each weed management system did not affect soil quality enough to affect yield of the following crop. However, growers implementing natural mulches for many years have increased soil organic matter to the extent that it may supply most of their fertility (Brown and Gallandt, in review). In main plots, where weed control was achieved with tractor cultivation but no hand-weeding, Critical Period plots from the prior year demonstrated a 22% loss of sweet corn yield ($F_{1,15}$ = 10.8, P = 0.004) compared to the other treatments, which yielded 16.6 Mg ha^{-1} on average. The yield loss reflects the increased weed emergence due to seed rain from the previous year (Table 1.2.) that contributed to end-of-season weed biomass of 685 g m^{-2}, while the other plots had lower weed biomass ($F_{1,15}$ = 27.14, P < 0.001), with a mean of 117 g m^{-2}. It is also possible that the reduced end-of-season soil nitrate level in the Critical Period system (Table 1.6.) contributed to the sweet corn yield loss. Enterprise budgets for the sweet corn operations showed that the yield loss in the plots where the Critical Period system was implemented the prior year resulted in a loss of over 2,500 USD ha^{-1} compared to the other systems (Brown et al. in review), and it is likely that this loss would have been greater in higher value crops.

Management Implications

The weed seed production of the Critical Period system had the greatest measured effect on the subsequent sweet corn crop; however, this system may be feasible if weed seed additions can be reduced by enhanced seed predation or subsequent cover cropping and stale seedbed periods. Conversely, weed control was greatest in the Zero Seed Rain system (Table 1.2.), which would likely reduce future weeding costs. Unfortunately, such preventative, long-term management is less common than seedling–focused management since growers often believe that weeds are inevitable (DeDecker et al. 2014; Wilson et al. 2015) perhaps due to an overestimation of seed longevity (Jabbour et al. 2014a). PE mulch resulted in higher end-of season nitrate levels (Table 1.6.) and warmed the soil (Figure 1.2.), which accelerated onion maturation (Table 1.3.). However, for onion, this increased soil temperature likely contributed to a yield loss in one year of two (Table 1.7.), thus, perhaps lighter colors should be used. It is likely that use of straw mulch in the paths between PE mulch could have been an effective means of weed control had the straw not contained oat seed. Similarly, the Straw Mulch treatment did not perform to its potential, given the volunteer oats. Perhaps farmers could grow their own straw to ensure seed-free mulch or store bales outdoors for the season prior to application to encourage fatal germination of seeds in the mulch. Generally, Straw Mulch and Hay Mulch treatments had high yields (Table 1.3.) and performed well in soil health parameters (Table 1.6.). Perhaps natural mulches could provide an alternative to cover cropping for growers reluctant to forego cash crops but interested in improving soil health. Furthermore, we have presented each system separately, but approaches could be combined to provide multiple benefits. For example, a Zero Seed Rain approach could be used simultaneously with natural mulching to achieve a seedbank reduction while benefiting from the soil aggrading properties of mulch.

We conclude that while each weed management system yielded equally in one year out of two (Table 1.3.), they present tradeoffs in effects on agroecology (Table 1.2.; Table 1.5.; Table 1.6.) and farm economics (B Brown, unpublished data). Our case studies of farmers who have adopted each weed management approach showed that the “best” system depends on grower management goals (Brown and Gallandt, in review). Therefore, it is our aim that this paper clarifies the ecological tradeoffs involved with each system so that growers may identify which approach best suits their management goals.

CHAPTER 2

AN ECONOMIC COMPARISON OF WEED MANAGEMENT SYSTEMS USED IN SMALL-SCALE ORGANIC VEGETABLE PRODUCTION

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Chapter Abstract

Organic farmers often have distinct weed management approaches. Farmers may cultivate during the “Critical Period” of the crop and ignore subsequent weeds; alternatively, their management may consider the long term, with a goal of “Zero Seed Rain.” A contrasting strategy is to suppress weed emergence with mulch, such as polyethylene (PE) film or hay. We used a systems comparison to provide farmers with a better understanding of the labor requirements and economic implications of each approach. In a test crop of yellow onion (*Allium cepa* L), weeding labor requirements were generally greatest for the Zero Seed Rain system and least for the Hay Mulch system. However, total labor costs were greatest for the Hay Mulch system and least for the Critical Period system. Zero Seed Rain required the most evenly spread workload, while the Hay Mulch was the most uneven. Unexpectedly, despite high weeding labor costs, enterprise budgets showed that the Zero Seed Rain system had the greatest net farm income (NFI). The Hay Mulch system also had high NFI, despite having the greatest labor and materials costs. The PE Mulch and Critical Period systems had comparably lower NFI, reflecting decreased onion yield, which was the most influential input variable. Mulched systems were slightly less

risky than cultivated systems. Subplots maintained in season-long weed-free conditions were less profitable than the respective main plots of each system. In a subsequent crop, NFI was decreased in plots where the Critical Period system had been implemented the previous year, likely due to weed seed rain and resulting weed competition. We conclude that while there may not be a single "best" system for all crops, for onion, the Zero Seed Rain and Hay Mulch systems performed favorably, and will likely provide continued benefits in terms of weed seedbank reduction and increased soil organic matter, respectively.

Introduction

Weed management approaches of organic farmers may be categorized into distinct overarching "philosophies" (DeDecker et al. 2014). Many organic farmers aim to control weed seedlings, while others have a more long-term weed seedbank perspective (Jabbour et al. 2014a). Farmers may also invest in mulch to suppress weeds (Baker and Mohler 2014). There are examples of successful farmers that emphasize each of these weed management approaches (Brown and Gallandt, in review). However, each approach likely has contrasting economic benefits and risks. Small-scale farmers may be unsure which approach is best for their situation, and correspondingly, where to invest their often-limited capital to improve weed management.

Most commonly, organic farmers aim to control weed seedlings (DeDecker et al. 2014). To minimize labor, these farmers may confine weeding events to the "critical period" of the crop, when weed-free conditions are required to avoid a yield loss (Knezevic et al. 2002; Nieto et al. 1968). However, if weeds are only controlled during the critical period, weed seed production is likely (Bagavathiannan and Norsworthy 2012; Brown and Gallandt, in review). Resulting seed rain can greatly increase the weed seedbank (Bond et al. 1998), contributing to increased weed emergence in subsequent crops (Norris 1999).

A zero seed rain approach has a more long-term, weed seed focus (Norris 1999; Gallandt 2014). This approach recognizes that seeds of many weed species are short-lived (Roberts and Feast 1972), therefore, preventing weed seed rain should cause a rapid decrease in the weed seedbank, and labor savings in subsequent years (Norris 1999). Indeed, some large-scale conventional vegetable farms in California have adopted this system to reduce their weed seedbanks, and ultimately, herbicide usage (Norris 1999). Nordell and Nordell (2009) popularized this approach for organic mixed-vegetable growers. After several years of weed seed prevention along with practices that deplete the weed seedbank, they observed a dramatic reduction in weed emergence, which allowed for reduced weeding labor.

A third distinct weed management approach involves use of mulch to suppress weed emergence. Mulching requires an early-season investment in labor and materials but results in reduced weeding labor later in the season. Polyethylene (PE) film mulch is commonly used to warm the soil and promote early yield of solanaceous (Cirujeda et al. 2012; Schonbeck and Evanylo 1998b) and cucurbitaceous crops (Farias-Larios and Orozco-Santos 1997; Kaya et al. 2005; Sanders et al. 1999). Additionally, the weed suppressive and moisture retaining properties of PE film have allowed it to increase marketable yields in other crops, such as onion (Vavrina and Roka 2000), cabbage (Trdan et al. 2008), and head lettuce (Brault et al. 2002). Natural mulches, such as hay, may also be used to suppress weeds. In organic bell pepper, profitability of production with PE and natural mulches was comparable to local conventional production using herbicides (Law et al. 2006). In organic tomatoes, a hay mulch system reduced weed biomass, and in some site-years resulted in a net labor savings (Schonbeck 1998), or greater yields compared to cultivated or PE mulch systems (Schonbeck and Evanylo 1998a).

We hypothesized that critical period weed control, zero seed rain management, and mulching with PE or hay would vary in labor requirements and profitability, representing contrasting economic benefits and risks. To test this hypothesis, we implemented each system in a replicated field experiment over two years. Unlike controlled experiments that vary a limited number of factors, systems comparisons aim to contrast whole-system effects. Such comparisons have been used to evaluate alternative production systems in vegetables (Chan et al. 2011; Halloran et al. 2005), small grains (Kolb et al. 2010, 2012), and corn-soybean rotations (Caldwell et al. 2014; Cox et al. 1999; Davis et al. 2012). These studies often utilize enterprise budgets to compare profitability. Additionally, risk analysis may be used to identify systems with less variable profitability, and therefore less risk (Ott and Hargrove 1989; Lu et al. 1999), and sensitivity analysis can determine the sensitivity of profitability to variation in input variables such as fertilizer prices (Ott and Hargrove 1989), seed prices (Lu et al. 1999), and crop yield (Chan et al. 2011). Our aim was to characterize the economics of several weed management systems used on small-scale organic farms to demonstrate the profitability, risk, and sensitivity of each system so that farmers may adjust their management appropriately. Related studies of the ecological differences between the systems as well as case studies of farmers who have implemented each system were presented elsewhere (Brown and Gallandt, in review).

Materials and Methods

We selected four weed management systems (detailed below) based on previous literature (Baker and Mohler 2014; DeDecker et al. 2014; Jabbour et al. 2014a) and prevalence of use in Maine, USA. Systems were compared in field experiments conducted in 2014 and 2015 at the University of Maine Rogers Farm in Old Town, ME (44.93°N, 68.70°W). A separate field was used for each year. Both fields were Nicholville very fine sandy loam. Weather was typical for the region throughout the study period, with average temperatures of 16.9 and 17.2 C and precipitation of 380 and 473 mm for 2014 and 2015, respectively (www.ncdc.noaa.gov). Yellow storage onions (cv. 'Cortland') were used as the test crop to represent a long-season, weed sensitive crop, for which weed management is often challenging.

Additionally, onions are commonly grown using each weed management system. Each system was implemented in a randomized complete block design with four replicates. Plots were 6.1 m long by 1.7 m wide. Buffer plots of the same dimensions were located on either side and a 2.4 m buffer was located on either end.

Using a combination of previous literature and interviews with farmers that have specialized in each weed management system (Brown and Gallandt, in review), we ensured that each system would be implemented in a realistic manner (Table 1.1.).

Critical Period Weed Control

In direct-seeded onions, the critical weed-free period is the first 56 to 84 d after emergence (Hewson and Roberts 1971; Menges and Tamez 1981; Wicks et al. 1973). Since our onions were transplanted, we used a 56 d critical period in 2014 (M. Guzzi, personal communication). During this period, hoeing was performed about every 14 d. Due to yield loss in 2014, the 2015 critical period was adjusted using growing degree-days, as described by Knezevic et al. (2002), which extended it from 56 d in 2014 to 78 d in 2015 (Table 1.1.).

Zero Seed Rain

With a goal of preventing all seed rain, these plots were hoed about every 14 d from transplanting until harvesting.

Polyethylene (PE) Mulch

Prior to transplanting, we applied embossed, black PE mulch (1.2 m wide, 0.025 mm thick, FedCo Seeds, Waterville, ME) with a mechanical applicator (Model 385PL, Bartville Welding Shop, Christiana, PA). A 5-cm wide trowel was used to make transplanting holes. Hoeing was used to control weeds in paths, while hand-pulling was used to control weeds emerging through planting holes.

Hay Mulch

Timothy (*Phleum pratense* L.) mulch hay was applied more than one month after transplanting (Table 1.1.) to allow time for the soil to warm. Hay was applied by hand at a rate of 20 Mg ha^{-1} (Schonbeck 1998). Hay was spread quickly in the paths, but in the beds it was carefully laid around the onions. Hand-pulling was used once to control weeds after the mulch was applied.

Additional treatments included a PE mulch system with oat (*Avena sativa* L.) straw mulch in the paths as well as an entirely oat straw mulch system. Unfortunately, the straw, which as purchased for this experiment, contained viable oat seed, which was able to emerge through the mulch (Brown and Gallandt, in review), required considerable time to hand-pull. Thus, these treatments were not included in this economic analysis.

Field Management

In early May of each year, primary tillage was performed with one pass of a rototiller, and secondary tillage with one pass of a field cultivator. Organic sources of fertility were applied prior to secondary tillage in quantities based on soil test recommendations (previously described on page 9). All fertility sources were measured and applied by hand.

Onions were sown in flats of organic potting mix (Light Mix, Living Acres, Inc., New Sharon, ME) in late February in a heated greenhouse. Immediately after tillage and application of PE mulch, onions were bare-root transplanted by hand at a spacing of two onions per planting hole, with holes 15 cm apart, and rows 30 cm apart. Diluted fish hydrolysate was applied directly after transplanting.

Un-mulched paths between onion beds were weeded with wheel hoes, while long-handled hoes were used closer to crop rows, and short-handled hoes were used in the crop row. Weeds in mulched areas were pulled by hand. Since plots were small, all laborers were instructed to work at a sustainable pace, commensurate with the pace of work in a larger field. Buffer areas were hoed following the Zero Seed Rain system.

Drip irrigation was used to maintain optimal soil moisture for each system. Irrigation lines (Triple K Irrigation, Morenci, MI) contained 16 mm diameter emitters, spaced every 30 cm, each with an output of 19 cc min^{-1}. Irrigation was applied weekly in the amount necessary to recharge the water deficit to a depth of 32 cm. The water deficit was determined weekly using a Delta-T HH2 Soil Moisture Meter with a 5.1 cm Theta Probe (Delta-T Devices, Burwell, UK) at four locations in each plot.

In 2015 only, sweet corn (*Zea mays* L. cv. Xtra-Tender 3473) was planted on June 4 with rows spaced 81 cm apart and plants 20 cm apart within rows. In this spacing, two rows were centered within the previous year's plots. Fertility was applied with pre-plant and sidedressing applications (as discussed on page 13). Weed control was provided by spring tine harrowing (Series 982, Type 3, Lely Industries NV, Maasland, Holland) on June 15; inter-row cultivations (Model 183, Case IH, Racine, WI) on June 15, June 25, and July 7; and disc hillings (Weedmaster, Elomestari Oy, Ltd., Kukkola, Finland) on June 25 and July 10. Weed-free subplots were additionally hand-weeded on June 19, July 6, July 20, July 31, and August 12. Yield was defined as the fresh mass of ears from both first and second harvests, occurring August 24 and September 2, respectively.

Economic Analysis

Economic modeling was primarily based on annual revenue, labor expenses, and materials expenses obtained from our field experiments. Additionally, assumptions of onion price, fuel usage, labor costs, and fixed costs were estimated (Table A.1.). The buildings and equipment were estimated base on the average size of an organic vegetable farm in Maine, USA, which is 1.42 ha (USDA NASS 2014). Annual revenue was determined by multiplying the wholesale onion price by the marketable onion yield. Marketable onion yield was measured by harvesting a 1 by 1 m quadrat, centered on the bed of each main plot and subplot. Harvest occurred on a per treatment basis when 70% of the onion leaves had folded. Harvested onions cured on mesh tables in a ventilated greenhouse for several weeks (Table 1.1.). Onions were weighed after tops and roots had been pruned, after curing. Visibly diseased onions were not included in yield data.

The amount of labor required for planting, weeding, mulching, and harvesting was recorded to the nearest second with stopwatches. Evenness of labor over the season was evaluated with Pielou's evenness index (*J'*) (Pielou 1975), which was calculated by separating labor for each system into 2 wk bins and using the equation:

$$J' = \sum \mathrm{p_i} \ln \mathrm{p_i} / \ln(S) \qquad \text{(Equation 2.1.)}$$

where p_i is the proportion of labor in each bin and *S* is the number of bins (10).

Expenses of all purchased materials were logged. Return over variable costs (ROVC) was calculated as the annual revenue minus related operating costs. Net farm income (NFI) was calculated as the annual revenue minus both the related operating (variable) costs such as labor, fuel, seedlings and fertilizer as well as the ownership (fixed) costs such as depreciation on equipment, fixed cost of land and taxes and insurance on fixed capital.

Economic risk and sensitivity analyses were performed using @RISK (Palisade Corporation, Ithica, NY) following Özkan et al. (2015). The @Risk software was used to define the distributions of several key input variables (Table A.1.) within our Excel (Microsoft Corporation, Redmond, WA) budget model for each weed management system. Using @Risk, 1,000 Monte Carlo iterations were run, in which values of input variables were randomly selected from pre-defined distributions. The input variables included fuel price, wage rate, hay price, onion yield, onion price, and labor required for planting, weeding, mulching, and harvesting. Economic risk was evaluated using the resulting cumulative distribution function (CDF) curves, which display the probability of achieving an NFI less than or equal to *x*. Evaluation of the differences between CDF curves were used to determine riskiness and stochastic dominance among the different systems (Hardaker et al. 2004), where system *A* is first-order stochastically dominant to weeding system *B* if the CDF for *A* is entirely to the right of the CDF for *B*. However, if two CDF curves cross, second-order stochastic dominance is determined by:

$$\int_{-\infty}^{x*} FA(x)dx \leq \int_{-\infty}^{x*} FB(x)dx \qquad \text{(Equation 2.2.)}$$

where if the area under the CDF for weeding system *A* is less than the area under the CDF for weeding system *B*, then system *A* is preferred to system *B* from an economic risk perspective. Both first- and second-order stochastic dominance assume farmers are risk-averse. Even though system *B* may have a slightly higher NFI than system *A*, the lower variability of system *A* may be preferred. Stochastic dominance with respect to a function analyses relax the assumption of risk aversion by ranking CDF curves depending on risk-seeking or risk-avoiding outlooks (Hardaker et al. 2004).

For each weed management system, sensitivity analyses are presented as tornado graphs, in which the high and low values of input variables from the Monte Carlo simulation were used to graph high and low NFI as other variables were held constant.

Statistical analyses were completed in JMP 10 (SAS Institute Inc., Cary, NC). A contrast was used to compare planting labor between systems with bare soil and the PE mulch system. Effects of weed management systems on labor requirements were evaluated with ANOVA. Years were analyzed separately due to multiple Year by Treatment interactions. Means comparisons were conducted using Fisher's Protected LSD. A significance level of 0.05 was used throughout the study. Data failing to meet assumptions were transformed as necessary or analyzed with the nonparametric Kruskal Wallis test (Kruskal and Wallis 1952) and pairwise Wilcoxon signed-rank test (Wilcoxon 1945).

Results and Discussion

Labor

Labor required to hand-transplant onions differed between plots with bare soil at the time of transplanting – Critical Period, Zero Seed Rain, and Hay Mulch systems – and those with PE film ($F_{1,42}$ = 14.01, P < 0.001), with labor requirements of 366 h ha^{-1} and 577 h ha^{-1}, respectively. Weeding, mulching, and harvesting labor differed by weed management system (Table 2.1.). Weeding labor was greatest for the Zero Seed Rain system. In the Hay Mulch system, application of mulch around the onions was very labor intensive. Conversely, in the PE Mulch system, mulch application with a tractor-drawn mechanical applicator was rapid and manual removal after harvest represented most of the mulching labor. As expected, harvesting labor was high for the Critical Period plots. Unexpectedly, PE Mulch also required a high amount of harvesting labor.

Table 2.1. Weeding, mulching, and harvesting labor required to grow onions using four weed management systems. Within each column, means followed by the same letter are not significantly different.

Weed management system	Weeding[a]		Mulching[b]		Harvesting[a]		Workload evenness[a]
	2014	2015	2014	2015	2014	2015	
	100 h ha^{-1}						J'
Critical Period	8.8 b	12.4 b	0.0 c	0.0 c	2.0 a	0.9 b	0.69 b
Zero Seed Rain	13.7 a	17.7 a	0.0 c	0.0 c	1.0 b	0.5 c	0.86 a
Polyethylene Mulch	9.9 b	10.8 b	0.5 b	0.3 b	2.0 a	1.2 a	0.66 b
Hay Mulch	7.5 b	7.7 c	9.4 a	6.9 a	1.0 b	0.8 bc	0.59 c
ANOVA							
P	0.004	<0.001	<0.001	<0.001	0.002	0.002	<0.001

[a] Means separated using Fisher's Protected LSD at P ≤ 0.05.
[b] Main effects tests performed with Kruskal Wallis tests (Kruskal and Wallis 1952) and means comparisons performed with Wilcoxon paired tests (Wilcoxon 1945), both at P ≤ 0.05.

Evenness of the workload over the season was evaluated using Pielou's evenness index (*J'*). Years were combined due to absence of a Year by Treatment interaction ($F_{1,3} = 1.48$, $P = 0.245$). The Zero Seed Rain system had the most even workload (Table 2.1.) reflecting the relatively constant weeding requirement (Figure 2.1.). Due to early-season weeding and mulching activities (Figure 2.1.), the Critical Period and PE Mulch systems required a less even spread of labor, and the Hay Mulch system required the most uneven workload (Table 2.1.). Harvest of the PE Mulch system occurred around one month earlier than the other systems (Figure 2.1.).

Economic analysis

Annual revenue was a direct reflection of onion yield (Table A.1.). In main plots and weed-free subplots, annual revenue of Zero Seed Rain and Hay Mulch systems was the greatest (Table 2.2.). Comparatively, annual revenue of the PE Mulch system was less, and the Critical Period system had the least annual revenue.

Labor expenses were least for the Critical Period system and greatest for the Zero Seed Rain and Hay Mulch systems (Table 2.2.). Material expenses were primarily fertility and seed starting supplies (Table A.3.). The major difference in material expenses between systems was mulch costs, which were 509 USD ha^{-1} for the PE Mulch system and 3,850 USD ha^{-1} for the Hay Mulch system. Ownership expenses were dominated by depreciation of equipment and facilities (Table A.3.). The only difference in ownership expenses between systems was the PE mulch applicator required for that system for 85 USD ha^{-1} per year.

Figure 2.1. Temporal spread of labor required to grow onions using each weed management system: Critical Period (A and B), Zero Seed Rain (C and D), Polyethylene Mulch (E and F), and Hay Mulch (G and H). Patterns within bars represent planting (gridlines), mulching (solid fill), weeding (dotted), and harvesting (diagonal lines).

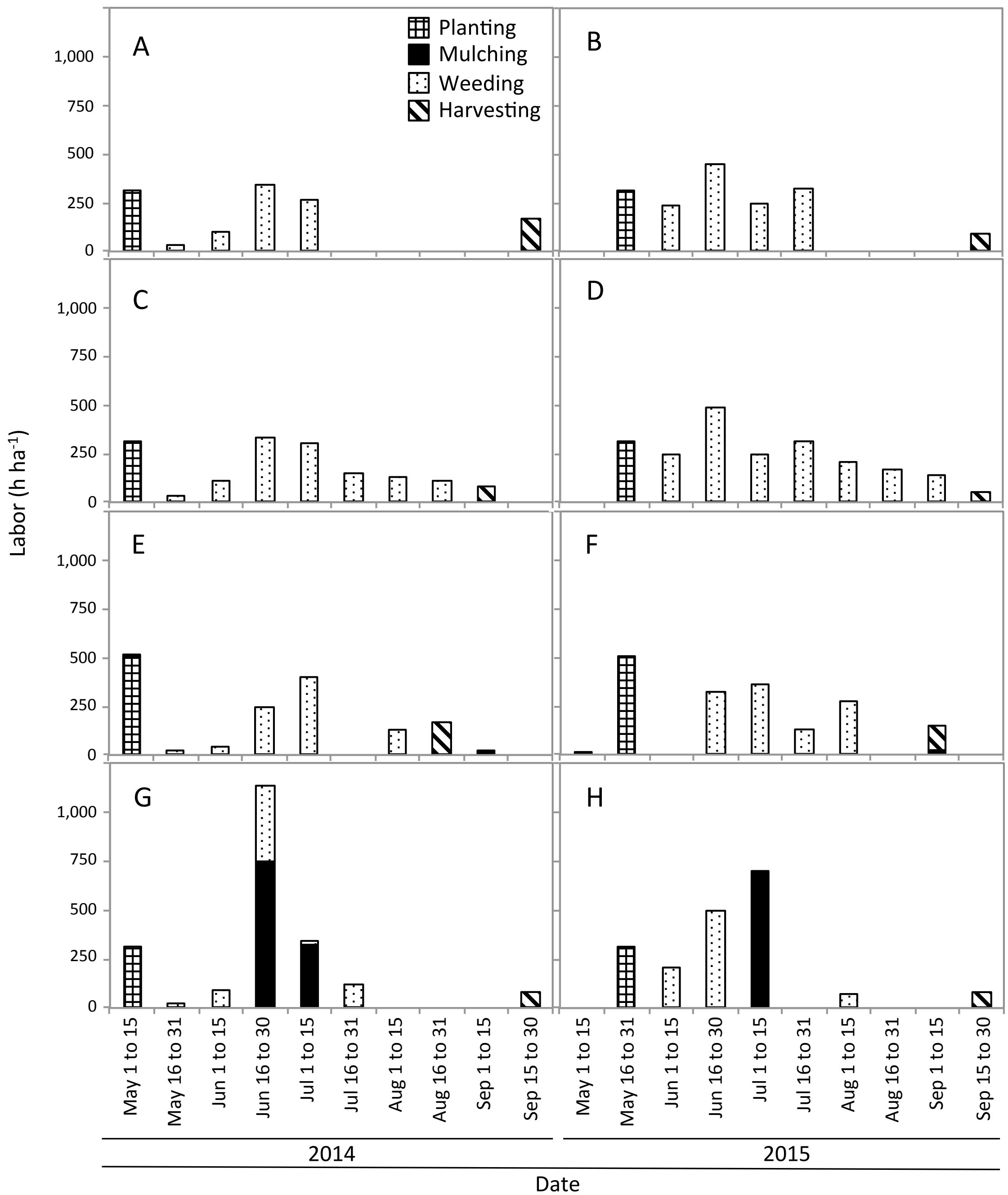


Table 2.2. Summary of enterprise budgets for four weed management systems. Annual revenue is a direct reflection of onion yield. Labor and material expenses were subtracted from annual revenue to calculate the return over variable costs (ROVC). Net farm income (NFI) was calculated by subtracting annual ownership expenses from ROVC.

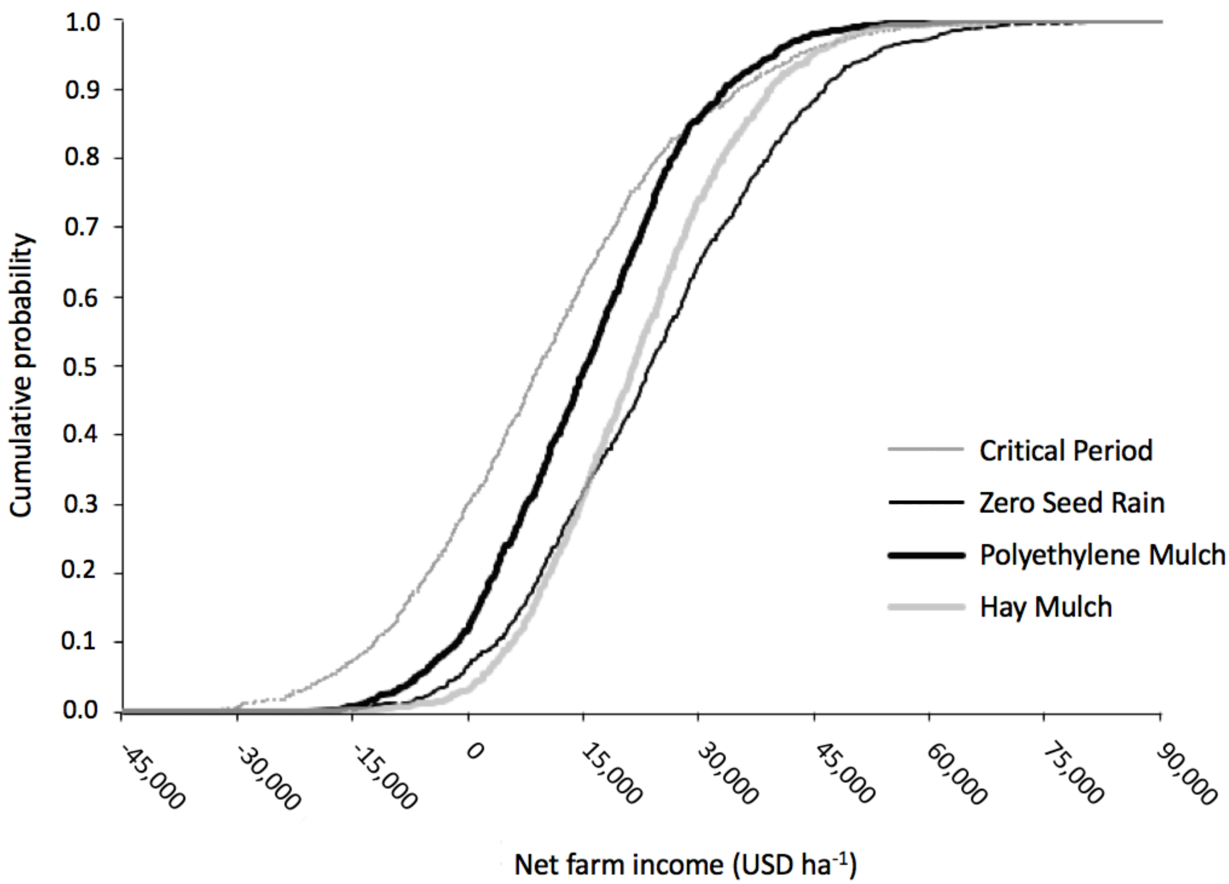
Weed management system	Annual revenue	Labor costs	Materials and other operating costs	Annual ownership costs	Return over variable costs (ROVC)	Net farm income (NFI)
			100 USD ha^{-1}			
Critical Period	522	154	149	117	219	102
Zero Seed Rain	703	194	149	117	360	243
Polyethylene Mulch	604	178	154	118	272	154
Hay Mulch	724	199	188	117	337	220

Net farm income was greatest for the Zero Seed Rain system followed by Hay Mulch, PE Mulch, and Critical Period systems, respectively (Table 2.2.). NFI reflected ROVC since it merely involved the extra subtraction of annual ownership costs, which were nearly uniform for all systems.

Risk Analysis was conducted with overlaid cumulative distribution functions (CDF) of NFI for the four weed management systems (Figure 2.2.). The Zero Seed Rain system demonstrated first-order stochastic dominance compared to the PE Mulch and Critical Period systems. The Hay Mulch system demonstrated first-order stochastic dominance over the PE Mulch system. The minimum possible NFI for the Critical Period, Zero Seed Rain, PE Mulch, and Hay Mulch systems were losses of 46,806, 20,633, 23,024, and 20,168 USD ha^{-1}, respectively, whereas the maximum possible NFI was 73,538, 102,393, 60,271, and 62,237 USD ha^{-1}, respectively. The wider ranges of the un-mulched systems caused their CDF curves to cross nearest mulched systems. The area under the CDF curve of the Critical Period system was greater than the PE Mulch system, indicating second-order stochastic dominance of the PE Mulch system.

Likewise, the Hay Mulch system exhibited second-order stochastic dominance over the Zero Seed Rain system.

Figure 2.2. Cumulative distribution functions of net farm income based on Monte Carlo simulation with 1,000 iterations of each weed management system.



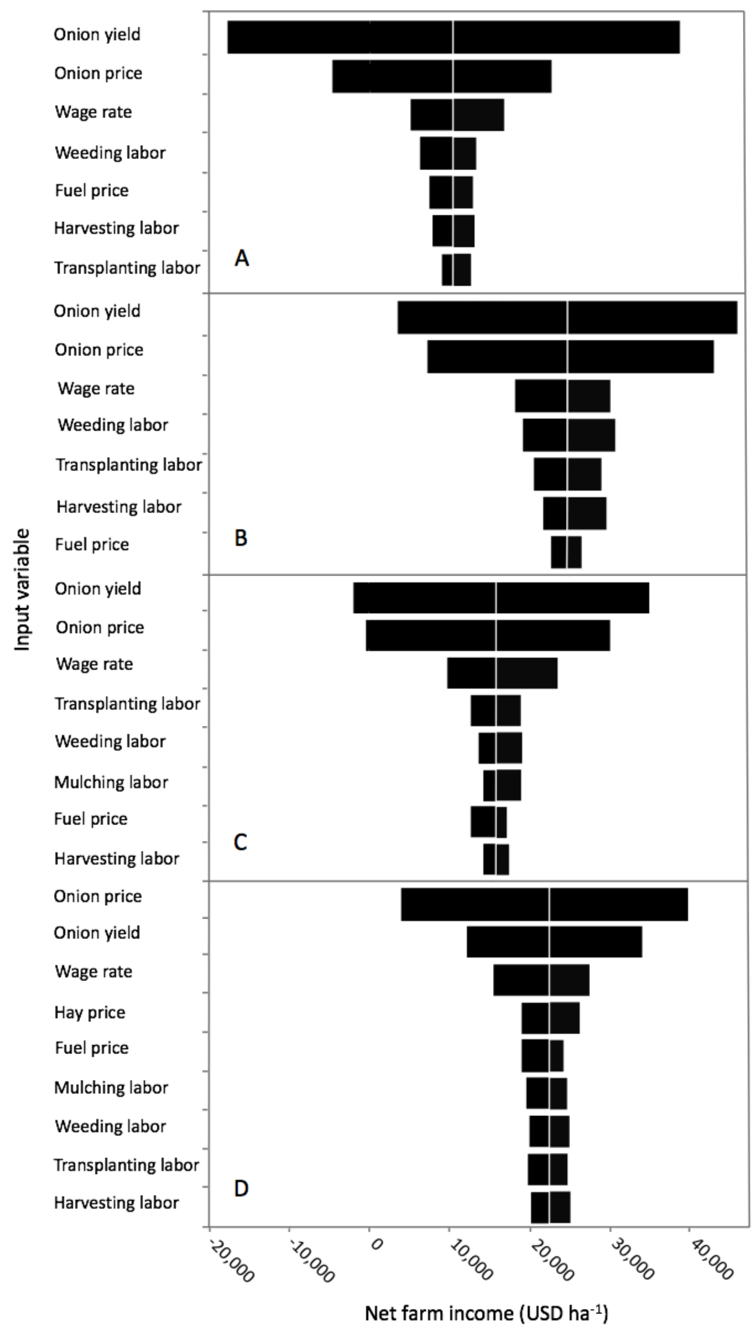
The sensitivity of NFI to changes in input variables is displayed by tornado graphs (Figure 2.3.). For most systems, NFI was most sensitive to onion yield, followed by onion price, and wage rate. The exception was the Hay Mulch system, in which onion price was the most influential determinant of NFI since onion yield was less variable in this system (Table A.1.). Net farm income was more sensitive to weeding and transplanting labor than harvesting labor in all systems. Mulching labor was a significant input variable for the mulched systems. Hay price was also an influential variable for the Hay Mulch system. Fuel price was minimally sensitive to fuel price for most systems.

In 2015, the yield of sweet corn grown in rotation after the onions was unaffected by system when weed-free conditions were maintained (Brown and Gallandt, in review). However, in sweet corn plots where weeds were managed with only early-season cultivation, Critical Period plots demonstrated a sweet corn yield loss, which resulted in an NFI loss of 2,187 USD ha^{-1} in the enterprise budget for sweet corn production, whereas the mean NFI of the other systems was positive at 337 USD ha^{-1} (Table A.3.).

Overall Performance of Each System

Our systems comparison showed that for onions, the Zero Seed Rain and Hay Mulch systems were most profitable despite incurring the greatest costs. These systems are considered long-term investments in reducing the weed seedbank (Norris 1999) and improving soil organic matter (Brown and Gallandt, in review), respectively. Therefore, it was unexpected that they would be the most profitable systems in the first season of implementation. Perhaps these systems would become even more profitable in subsequent years. Depending on the tillage system (Anderson 2005), several years of intensive Zero Seed Rain management can reduce weed emergence (Nordell and Nordell 2009) to the extent that one farmer with a Zero Seed Rain approach is now able to manage a 4-ha mixed-vegetable farm with only two additional workers (Brown and Gallandt, in review). Alternatively, hay mulching may improve several measures of soil health (Brown and Gallandt, in review; Schonbeck and Evanylo 1998b). Increased soil organic matter from many years of hay mulching may even provide sufficient crop fertility (Brown and Gallandt, in review).

Figure 2.3. Tornado graphs displaying the sensitivity of net farm income to variation in selected input variables for each weed management system; Critical Period (A), Zero Seed Rain (B), Polyethylene Mulch (C), and Hay Mulch (D). Plotted net farm income was calculated by using the extreme values of 1,000 Monte Carlo sampling iterations from each input variable, while all other variables remained at baseline levels.



The profitability of the Zero Seed Rain and Hay Mulch systems likely relates to these systems providing the best weed control (Brown and Gallandt, in review) and onions being a weed sensitive crop (Bond and Burston 1996; Ware and McCollum 1975). Indeed, the onions yielded highest in these systems and NFI was most sensitive to onion yield and price (Figure 2.3.). Similarly, in organic mixed-vegetable production, Chan et al. (2011) observed that yield and crop price were more important determinants of profitability than input costs.

Sensitivity of NFI to wage rates (Figure 2.3.) reflects the high labor costs involved with these systems. The Zero Seed Rain system required the most weeding labor (Table 2.1.), whereas the Hay Mulch system had the greatest total labor expenses (Table 2.2.), consistent with the experience of farmers that have implemented these systems (Brown and Gallandt, in review). The evenness of the workload in the Zero Seed Rain system (Table 2.1.) would perhaps be desirable for a farm with a steady but limited labor pool. A potential conflict of management priorities may arise in late-summer, when the short photoperiod encourages many summer annual weeds to set seed quickly (Gifford and Stewart 1965; Weaver and McWilliams 1980), while harvest operations also need to be conducted. Conversely, the uneven spread of labor in the Hay Mulch system would perhaps be best suited to farmers with ample access to seasonal labor, who could hire a short-term crew to complete the early-season mulching. Alternatively, farmers may be able to accomplish mulching by staggering planting dates so that it could take place over a more protracted period. Mulching labor could possibly be reduced in warmer growing regions, where warm soil temperature would allow for mulch application prior to transplanting. However, natural mulches applied prior to transplanting may not provide season-long control (Law et al. 2006), thus, increased application rates may be necessary.

In the Hay Mulch system, NFI was sensitive to hay price (Figure 2.3.), reflecting the variability of this input. Hay may be procured for free in the case of spoiled, mulch hay, or bought for as high as 0.28

USD kg^{-1} (Table A.1.). Law et al. (2006) found similar sensitivity to price of natural mulches in bell pepper production; when mulch was obtained for free, profitability was similar to conventional production, but profitability was greatly decreased when mulches were purchased. Hay mulch costs could perhaps be decreased if farmers grew their own, which would also allow them to ensure minimal weed seed contamination. Alternatively, in New England, USA, municipal leaf collections may be inexpensively delivered to farms and used in a similar manner as hay mulch (T. Roberts, personal communication).

The PE Mulch system did not perform as favorably as expected. It was unexpected that onion yield did not increase in PE Mulch, since many crops (Kaya et al. 2005; Trdan et al. 2008; Zhang et al. 2007;) including onions (Vavrina and Roka 2000), have shown a positive yield response. Yield loss in 2014 was likely due to warmer soil causing early senescence (Brown and Gallandt, in review). In some crops, like tomatoes, early yield would likely allow for premium prices. However, for storage onions, early yield is unlikely to increase profitability since this type of crop can be stored almost all year.

The increased transplanting labor in the PE Mulch system and the added task of PE film removal were also noted by Schonbeck (1998) to negate any labor savings compared to a hay mulch system. However, some small-scale growers have invested in water-wheel transplanters (Rain-Flo Irrigation, East Earl, PA), which have increased speed of transplanting in PE film (J. Kafka, personal communication). Mechanical PE film removal equipment is also available (CropCare, Lititz, PA).

The PE Mulch system required more weeding labor than expected (Table 2.1.), due to weeds emerging through the planting holes, which necessitated hand-pulling. Smaller planting holes may have decreased the necessity of hand-pulling but would likely have increased transplanting labor. Our recommendation is that black PE film be used for heat-loving crops, which are typically more widely spaced than onions, thereby providing less opportunity for weeds to emerge through planting holes.

The Critical Period system incurred a yield loss in 2014, but in 2015 the period was adjusted using growing degree-days, following Knezevic et al. (2002), and there was not a yield loss (Brown and Gallandt, in review). Theoretically, critical period weed management should not exhibit a yield loss (Nieto et al. 1968). However, the two years were combined in the economic analysis because the length of the critical period may change based on weather or other factors (Knezevic et al. 2002), which may not be accounted for by small-scale growers (M. Guzzi, personal communication).

In addition to having the lowest mean NFI (Table 2.2.), the Critical Period system had a wide range of possible NFI (Figure 2.3.), indicating higher risk. Despite the unfavorable performance of the Critical Period system, it is commonly used by farmers (Jabbour et al. 2014a), highlighting their keen interest in reducing labor costs. Indeed, the weeding labor reduction provided by a Critical Period approach offers a "huge, practical benefit" according to one farmer (M. Guzzi, personal communication). Additionally, in more weed competitive vegetables, such as cabbage or cucumber, the critical weed-free period is a shorter duration (Weaver 1984), thereby offering more labor savings than in onions. Furthermore, the effect of increased harvest time due to weed interference would likely be lessened in larger, or more prostrate crops.

Perhaps the most important effect of the Critical Period system was the abundant weed seed rain, which increased weed competition in the subsequent sweet corn crop (Brown and Gallandt, in review), and reduced profitability (Table A.3.). Therefore, thresholds for determining the level of necessary weed control based solely on yield may not be advantageous (Norris 1999). However, with sufficient farmland, farmers may use frequent cover crops in their rotation to bring the weed seedbank back down to a manageable level (Brown and Gallandt, in review).

Overall, a single management system is unlikely to be preferable for all crops (Chan et al. 2011). Therefore, it is not our aim that farmers adopt a single "best" approach, but for farmers to understand the benefits and risks of each weeding system so that each may be used appropriately. Our research with onion, representative of a long-season, weed-sensitive crop that grows well in temperate climates, has demonstrated that the more intensive systems – Zero Seed Rain and Hay Mulch – performed favorably. However, in the context of a mixed-vegetable farm, the most successful approach may be to use all systems concurrently, with each system being implemented according to the crop, labor and input availability, and farmer management goals.

CHAPTER 3

TO EACH THEIR OWN: CASE STUDIES OF FOUR SUCCESSFUL, SMALL-SCALE ORGANIC VEGETABLE FARMERS WITH DISTINCT WEED MANAGEMENT STRATEGIES

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Chapter Abstract

Farmers often have distinctive weed management strategies that have developed as a result of their unique perceptions and prior experiences. To characterize the motivations and risks of different weed management strategies, we conducted case studies of small-scale, diversified organic vegetable farmers representing strategies focused on (i) weed seedling management, (ii) seedbank management, or (iii) weed prevention with polyethylene (PE) or natural mulches. Mark Guzzi tends to manage weed seedlings in the so called "critical weed-free period," which minimizes crop yield loss but often allows weeds to set seed, contributing to an abundant weed seedbank. In contrast, Tom Honigford aims for zero seed rain, a strategy that required a large early-career labor investment to prevent weeds from setting seed, but has paid off with greatly reduced weed pressure in subsequent years. Dave Colson utilizes PE mulch on many crops to reduce weeding labor, which is especially beneficial in the early-season when the need to plant other crops formerly prevented him from weeding. Tom Roberts uses natural mulches to suppress weeds, conserve soil moisture, and build soil health. Regarding drawbacks to their strategies, Guzzi spoke of the high weeding labor required for weed sensitive crops, Honigford was somewhat concerned with decreased soil quality due to frequent cultivation, Colson mentioned the

environmental cost of using a petroleum-based product, and Roberts emphasized the high amount of labor required to collect and apply natural mulch. Though each farmer utilized knowledge of the weed seedbank in their management, weed seedbank densities ranged from 3,065 seeds m^{-2} (Honigford) to 38,482 seeds m^{-2} (Guzzi). Soil organic matter was very high for Roberts, reflecting his regular addition of natural mulches. Pairwise comparisons of select management-related criteria showed that Guzzi placed most importance on reducing weeding labor, Honigford valued the weed seedbank, Colson placed nearly equal importance on all criteria, and Roberts most valued soil quality. These successful, highly-regarded farmers demonstrate that there is not a clear, single "best" weed management strategy for small-scale organic vegetable growers, but beginning and experienced farmers alike may benefit from a thoughtful analysis of their weed management philosophies and the motivations and risks of their foundational strategies.

Introduction

Organic farmers often have distinct attitudes related to weed management (Dedecker et al. 2014). They may focus on short-term control of weed seedlings, longer-term weed seedbank management (Jabbour et al. 2014a,b), or weed suppression with mulch (Baker and Mohler 2014). Motivations driving each of these fundamentally different weed management strategies vary widely. For example, farmers focused on management of weed seedlings often prioritize weed control during the critical weed-free period (Jabbour et al. 2014a,b), the period when weed-free conditions need to be maintained to avoid crop yield loss (Knezevic et al. 2002; Nieto et al. 1968). However, this strategy often allows late-season weeds to set seed, resulting in abundant seed rain and a high weed seedbank (Norris, 1999).

Conversely, farmers with a seedbank management philosophy emphasize the risks of weeds and employ more preventative techniques (Jabbour et al. 2014a,b). For example, controlling weeds before they set seed would lessen weed emergence in subsequent years and reduce weed control costs (Norris, 1999). Such a zero seed rain strategy has been used to effectively reduce the weed seedbank (Gallandt, 2014; Riemens et al. 2007).

A third distinct group of farmers aim to front-load their weed management efforts using mulch to suppress weeds (Baker and Mohler 2014), a strategy generally employed in high-value vegetable crops. In northern temperate regions, black PE mulch is often used for its soil warming properties; however, it is also valued for weed suppression and soil moisture retention (Lament 1993), and can increase yields in a variety of vegetable crops (Kaya et al. 2005; Vavrina and Roka 2000; Zhang et al. 2007). In Ohio, USA, farmers discussed the potential for black PE mulch to save labor and weed control costs, but also the risk of having to control weeds in the pathways and planting holes (Zwickle 2011). Natural mulches, such as hay or tree leaves, may also be used to suppress weed growth. Natural mulch application requires a large early season investment in materials and hand labor, but there is a psychological boost to farm workers in knowing that little subsequent weeding is required (P. Arnold, personal communication). One concern about natural mulches among farmers is the risk of bringing in weed seed (Zwickle 2011), which farmers address by knowing the mulch source or harvesting it themselves.

Each of these fundamental approaches to weed management has unique benefits and drawbacks. Since farmers are strongly influenced by the experience of other farmers (Rogers 1988), it is the intent of this paper to showcase farmer motivations for each strategy, thereby informing beliefs and influencing weed management decisions (Wilson et al. 2009; Zwickle 2011) by affecting perceptions of risk and how to mitigate that risk (Slovic 1987). To do so, we present case studies of successful farmers that have specialized in each approach in order to characterize the motivations and risks of each management strategy.

Materials and Methods

A farmer representative of each of the four weed management strategies was selected in July 2014 based on their interest and wilingness to participate, involvement with previous studies (i.e., Jabbour et al. 2014a,b), and the authors' familiarity with the farmers' practices. Farmers were all small-scale, organic, mixed vegetable growers located in northern New England. In September 2014, ten soil cores to a depth of 18 cm were collected from a representative field at each farm. Homogenized samples were sent to the University of Maine Soil Testing Service for soil organic matter (SOM) testing. An additional, ten soil cores were obtained using a bulb planter (Yard Butler IBPL-6 Bulb and Garden Planter, Lewis Tools, Poway, CA), 8 cm diameter, inserted to a depth of 10 cm, to perform germinable weed seedbank assays (Gallandt et al. 1998). Following Ryan et al. (2010), soil was placed in 4 L resealable plastic bags and transported in an insulated cooler to storage in dark conditions at -12 C. Bags were removed from storage on May 1, 2015 and allowed to thaw for 48 h before contents were spread on 51 by 51 cm flats over a 2.5-cm layer of vermiculite. Flats were watered regularly to encourage germination. Common seedlings were identified to species or genus, while less common seedlings were recorded as "other broadleaf" or "other monocot." Seedlings were removed after being identified. When germination slowed, flats were allowed to completely dry so that the hardened soil could be lifted from the vermiculite, placed in a bucket, mixed, returned to the flat, and watered to encourage a new flush of germination. Five such cycles occurred during the assay period of May 1 to September 30, 2015.

Farmers were interviewed in March 2015 after obtaining approval from the Institutional Review Board for the Protection of Human Subjects (IRB) (Figure A.1.). Following the interviews, permission from the farmers and IRB was granted to disclose identities. The four participants were each compensated 250 USD for their time. Interview questions were developed to highlight key differences between farmer weed management strategies. This research aimed to capture individual narratives of the practices and motivations related to each weed management strategy. The same questions (Table A.4.) were asked in all interviews in a semi-structured format (Bernard 2011) that allowed for occasional follow-up questions.

Following the Analytic Hierarchy Process (Saaty 1982), the interviews also included a series of pairwise comparison questions to determine importance of four management-related criteria to the farmers. The four criteria were: weeding labor, the weed seedbank, environmental sustainability, and soil quality. Each possible pair of criteria were presented to farmers with the instruction to rank the pair on a scale of zero to ten with zero meaning the first term is extremely important and the second term has no importance, and visa versa, and with a rank of five meaning that the two terms are equally important. The weights of the individual criteria were calculated by creating a normalized comparison matrix, then dividing each value by the sum of its column, and taking the mean of each criteria row.

Interviews were conducted by telephone, were around one hour in duration, and were recorded using a digital voice recorder. Interviews were transcribed manually and checked for accuracy and consistency by the authors. Prior to publication, all interviewed farmers approved the final draft.

Results and Discussion

Participating farmers all owned and managed small-scale, diversified organic vegetable operations. Along with farmers' different weed management philosophies and strategies, farms varied in their soil type, numbers of workers, land area in cultivation, cover crop usage, and seasonal workload (Table 3.1.). Each of the case study farmers is well-established, having a minimum of 17 years of experience, and is highly regarded in the organic farming community. Each manages weeds in a distinct manner and, as will be discussed, the factors that influenced the formation of their weed management philosophy ranged widely.

Table 3.1. Summary of soil texture, farm size, and land use for case study participants representing each weed management strategy.

Farmer	Weed management strategy	Soil texture	Seasonal workers	Land in cultivation	Land in summer cover crop	Land in winter cover crop	Busiest time of year for farm operations
			no.	ha	%	%	
Mark Guzzi	Critical period	Silt loam	10	10	28	40	All season
Tom Honigford	Zero seed rain	Sandy loam	2	4	14	75	Aug-Sep
Dave Colson	Polyethylene mulch	Loam	5-7	4	50	90	May and Sep
Tom Roberts	Natural mulch	Clay loam	3-12	2	15	20	Aug–Sep

Mark Guzzi – Critical Period Weed Management

Guzzi uses a mix of mechanical cultivation and hand hoeing, often focused on the early growth period of his crops. Guzzi sometimes confines weeding events to the early season to save labor (*in sensu* Knezevic et al. 2002). He says,

> *"…crops can tolerate some weed pressure, especially later on in the season and so it becomes an issue of whether those weeds are going to interfere with harvest or not. There is a window when the competition is the most and it tends to be when the crop is small. You get the crop passed a certain stage and then the weed pressure is going to make less of a difference on the ability of that crop to grow. That doesn't necessarily mean that those weeds aren't going to be a problem later on [due to seed rain]."*

Regarding how Guzzi established his current weed management strategy, he recalled,

> *"It's very short term thinking… the [previous owner] had allowed the weed seedbank to grow and become a very significant problem. So when we got here… we got used to growing in very weedy fields. Our level of tolerance is no doubt higher than it should be… We created this farm business with all of these markets and expectations despite the fact that we were totally contaminated with weeds. I recognized…the smart thing to do would be to have done a Nordell-type approach where we would have taken that ground and exhausted the weed seedbank before expanding production… [Now] there is a psychological barrier that I feel to scaling the whole thing back and going to the Nordell approach."*

Guzzi is referring to Eric and Anne Nordell, who helped popularized weed seedbank management approaches (Gallandt 2014; Nordell and Nordell 2009). Guzzi's explanation mentions short-term thinking, which has been found to be correlated with high weed seedbanks (Jabbour et al. 2014b).

Tom Honigford – Zero Seed Rain

Honigford has a very low tolerance for weeds. He uses mechanical cultivation every 10–14 days until crops grow too large to be cultivated. Shortly after each mechanical cultivation, scuffle hoeing (also called stirrup hoeing) is used to control weeds that tractor cultivation missed. In this process, weeds in close proximity to the crop are pulled by hand, and any crop plants that were buried by cultivation are uncovered. After crops are too large for tractor cultivation, he continues to cultivate with hand tools until late in the season when weeds no longer have time to produce seed before the crop is harvested and tilled. Early career weed control efforts have led to a dramatic reduction in the size of his weed seedbank (*in sensu* Norris 1999), which means that weed seedling densities are relatively low, and following even moderately effective cultivation, hand-weeding is minimal. When asked what motivated him to develop such a low weed threshold he joked,

> *"probably because I'm German – There will be order! I just like the look of a clean field. [Weeds] never get that big in my operation. I nail those little [expletive] as soon as they come out of the ground! ... After a while I said 'Hey, wait a minute, this is actually working! … I've front loaded the process, I worked my ass off over those first few years, killing all those weeds… Every year I find that I weed less than I did the year before because I don't have any weed seed rain anymore."*

Dave Colson – Polyethylene (PE) Mulch

Colson uses a diverse array of ecologically based weed management practices. We focus on Colson's use of black PE mulch for many of his crops. His crops grown with PE mulch generally do not need to be weeded in the beds. Exceptions include some long-season crops, which may require hand pulling to control the weeds emerging through the planting holes, but this can often be done during harvesting operations. He mostly uses mechanical cultivation for the paths with the addition of hand hoeing to control edges of PE mulched beds. For crops in the Cucurbitaceae family he uses natural mulch for the paths in between the PE to suppress weeds and to keep the fruit cleaner and easier to find. Colson recounted the factors involved with his increased use of PE:

> *"We started using black [polyethylene] because we wanted to get more heat units on heat-loving crops. The problem is in the spring, you're so busy getting so much planted that by the time you hit June you're ready to go back and start doing maintenance on the stuff you've put in. Often a lot of stuff we wouldn't have thought about putting [polyethylene] on are filled with weeds, like those early brassicas… the reason for putting them in [polyethylene] was so we could put the hand weeding time into things like [planting or weeding the direct seeded crops]."*

Tom Roberts – Natural Mulch

Roberts applies hay or tree leaf mulches to most crops by hand after they have grown large enough to avoid being smothered. He mows hay before it sets seed with a flail mower to produce finely chopped mulch that is applied by hand around delicate or closely spaced crops, like onion. He uses a string-trimmer to harvest irregular areas inaccessible to the flail mower, and uses this mulch, which includes longer pieces, on crops less prone to being smothered. He also accepts his town's municipal tree leaves to use as mulch. Whole leaves are used in paths but leaves need to be shredded for use in beds to avoid matting and not letting oxygen to roots. Many of his crops are mulched immediately after transplanting but some, like onions, are too small to be mulched initially and require weeding before they can be mulched. Some hand pulling may also be necessary to control any weeds that emerge through the mulch. Roberts explained the factors that led him to include natural mulch as an integral part of his farming system:

> *"Several things, one is we have mulch available and if something is available to boost our organic matter we ought to be using it. It also retains water… We don't have a lot of water available to us… So that water retention is really important to us. The fact that it suppresses weeds is a real bonus… It's not just for weed suppression, if that's all it did, the cost of the hand labor would be hard to justify."*

As will be discussed in the following sections, farmers ranged widely when speaking about benefits and drawbacks of their strategies, required equipment, crop rotation, response to wet weather, and problem weeds. Farmers also had differing weed seedbanks, soil organic matter, and ranked importance of criteria related to management.

Additional Benefits of Each Strategy

When asked if there were any additional benefits to their weed management strategies, Guzzi replied that the greatest benefit of prioritizing weeding during the critical period was the labor savings but he also mentioned the addition of the weed biomass that is incorporated into the soil every year, the weeds acting as an indicator of soil health, and the food and habitat that weeds provide to birds, mice, and beetles. While weeds acting as an indicator of soil health is controversial (Kopittke and Menzies 2007; Tillman et al. 1999), the ecosystem services provided by weeds is well-documented (Marshall et al. 2003; Petit et al. 2010). Honigford reported that customers rave about the taste of his produce, which he attributes to the lack of weed competition. Additionally, he never applies mid-season fertilizer, which he believes he can omit because of the lack of weed competition. As a benefit to using PE mulch other than labor savings and soil warming, Colson mentioned that weeds likely germinate in the warm, moist environment under the mulch but since most are unsuccessful at emerging through the mulch, it may help to reduce the weed seedbank. He also indicated that since the mulch helps the soil retain moisture, it lessens the need to irrigate. Likewise, Roberts noted that increased water conservation due to the natural mulch is one of the main benefits. He also values the increased SOM due to the mulch applications. Roberts believes his high SOM buffers the pH, decreases nutrient leaching, and improves the soil structure. Roberts is gradually reducing the amount of compost he applies with the expectation that the high SOM will be sufficient to provide most of his fertility. Indeed, for every 1% of SOM, 22 to 34 kg N ha^{-1} can become available during the growing season (Grubinger 2005). Roberts mentioned that nutrients may wash down from the mulch to the plant roots during rains. This may be possible for some nutrients, but Ferreira et al. (2015) found that nitrogen in rotary mowed legume mulch is lost to volatilization if not incorporated into the soil. However, natural mulch can result in nitrogen savings (Singh et al. 2015), attributed to decreased water evaporation and moderation of soil temperature, which may reduce nitrogen mineralization.

Drawbacks of Each Strategy

Guzzi noted that the increased weed emergence that results from his letting weeds go to seed is detrimental in several ways. He explained,

> *"in some crops that have less tolerance to weed pressure – and a lot of those are valuable crops that we want to keep in the mix – we would make more money off them if we didn't have to spend the time we did weeding them. Fall carrots being an example, onions being an example, salad mix being an example. The weeds themselves create competition but they also do other things, they can reduce airflow*

in the crop resulting in disease problems, they can host insects, they can provide habitat for rodents. The weeds can be more of an issue besides just being direct competition."

Regarding drawbacks to Honigford's frequent cultivation, he mentioned the possible negative effects of soil disturbance but was optimistic that since it was merely shallow disturbance it is not as detrimental as tillage. This is consistent with previous work showing that organic farmers using extensive cultivation rarely considered risks to their soil (Jabbour et al. 2014b; Riemens et al. 2010). He also cited his profitability as evidence that what he is doing is working. He joked, "I've read articles about the starving farmer…and I'm not one of them. I'm not taking three trips to Bermuda every year, but I'm not crying in my soup either." Colson spoke of the environmental costs of plasticulture, saying, "[Polyethylene] is one of those tradeoffs. If I didn't have to use it, I wouldn't. I don't like using a petroleum product and having all of that to throw away every year." He also talked about the extra management step of applying the PE and keeping track of where it is ready for planting. Roberts acknowledged that soil cooling is a drawback of the mulch, but for crops that thrive in heat, like tomatoes, he waits until early July to apply the mulch and at that time the soil is sufficiently warm and the mulch begins to be critical for moisture retention. But he says that, "The biggest drawback of [natural] mulching is all the labor involved. Growing it, harvesting, moving it to the field and then actually applying it." He also estimates that growing the mulch requires five to ten times as much land as the mulched area. For these reasons, perhaps natural mulching is best used on a small scale.

Required Equipment

When speaking about the equipment critical to his weed management strategy, Guzzi cited his spring tine cultivator, his collection of sweeps and knives, and his Reggie weeder (Univerco, Quebec, Canada), which is a powered, rotating set of tines that a rear operator can move in and out of the crop rows. Honigford has six different cultivators, each best suited to different conditions (Bowman 2002). He explained, "none of them are high end, but each does something a little different…they work under different conditions and different types of weeds… [which] gives me the ability to be more flexible." Colson's main piece of necessary equipment was a single bed PE mulch applicator. He also has a toolbar with gangs of sweeps set to cultivate the pathways. Roberts initially used a rotary mower to make his hay mulch but it cut the pieces too long. He wanted finer mulch that "you don't have to put it on as thick because it fits around the plant better, bigger pieces just don't pack as well so they don't stay as well. So four years ago we bought a flail mower. It works really well. We've replaced [the rotary mower]."

Crop Rotation and Cover Cropping

Guzzi's crop rotation is adjusted to avoid planting weed sensitive crops in areas of heavy seed rain from the year before. In years of extremely heavy seed rain, he sometimes uses a moldboard plow to bury weed seeds deeply. At greater soil depth, germination may be inhibited (Holm 1972; Stoller and Wax 1973) and weeds that do germinate are less likely to successfully establish, but seed decay may be slowed (reviewed by Mohler 1993), meaning that the buried weed seeds would likely remain problematic if returned to the surface. Honigford makes frequent use of cover crops but warned that "I will never let a cover crop go for more than a month or two… because then weed seeds form…Nothing ever stays untilled for more than a couple of months, otherwise the weeds will [go to seed]." Colson's crop rotation is dependent on the goal for that ground. If the goal is to reduce the weed seedbank he can increase the number of bare fallow periods, whereas if the weed seedbank is sufficiently low he uses more legume-based rotations to increase fertility. He notes,

> *"the critical part is not what you're doing for weeds in the year that you're growing the crop, it's the management that leads up to growing the crop that has the greatest effect on the weed seedbank and thus the type of control we decide to do.*

Often we'll anticipate going into a less weed tolerant crop and so we'll try and reduce that weed seedbank a year or two ahead."

Roberts uses summer cover crops every four years, which are mixed with bare fallow periods to promote flushes of weed germination that are controlled prior to planting the subsequent cover crop. Roberts rarely plants winter cover crops because of the sufficient cover provided by the mulch, even after it has been disked.

Effects of Wet Weather on Operations

Most farmers stressed that cultivation is typically not effective in wet weather, which is a well-documented effect in the literature (Cirujeda and Taberner 2004; Evans et al. 2012; Terpestra and Kouwenhoven 1981). Guzzi noted that wet weather can cause him to miss the opportunity to cultivate while weeds are small. This was also the main perceived risk of cultivation described by previously interviewed organic farmers in this region (Jabbour et al. 2014a). Guzzi also noted that if there is a stretch of wet weather toward the end of the spring planting season, it is more important for him to finish planting than to catch up on weeding, so those unweeded crops may need to be ignored. Honigford watches the weather forecast closely. Due to his high post-harvest refrigeration capacity, he has the flexibility to weed during the dry part of the week when weeding is most effective and harvest during the cool or wet part of the week. Colson recalled that "it used to always be that... we'd prep the beds, have them all ready for the [polyethylene], wait for a good soaking rain, then we would cover the beds to seal some moisture in. The last few years it seems like we're trying to find a dry period in covering the beds so they aren't getting waterlogged." Roberts mentioned that in the wettest recent year he was worried about mulched crops being too wet, but it was not a problem.

Weed Species

Most of the farmers highlighted crabgrass (*Digitaria* spp) and hairy galinsoga (*Galinsoga ciliata*) as their most problematic species, consistent with previous interviews of northern New England organic growers performed by Jabbour et al. (2014b). Honigford has a "most wanted poster" displayed for hairy galinsoga at his farm to educate employees. Although he does not have much hairy galinsoga, he wants to prevent it from establishing. He also instructs employees to hand pull common purslane (*Portulaca oleracea*) and walk it out of the field due to his previous experience in which he would pull it up but it would produce viable seed prior to desiccation. Indeed, since common purslane can self-fertilize (Zimmerman 1969), senescent plants can produce viable seed if flowering has occurred prior to frost (Miyanishi and Cavers 1980). It can also spread vegetatively from stem cuttings (Proctor et al. 2011). Colson struggles with summer annual grasses that grow and set seed quickly. They also form thick clumps in the paths that are difficult for him to control with cultivation. Roberts also struggles with summer annual grasses. Possibly contributing to the problems of Colson and Roberts with grasses, Brown and Gallandt (in review) noticed that monocot morphology may allow it to emerge through the mulch. Roberts noted that summer annual broadleaf weeds such as hairy galinsoga are easily suppressed by his mulch. He recognizes that hairy galinsoga seeds have a short half-life, thus a thorough mulching in the year following seed rain will cause many of the seeds to perish.

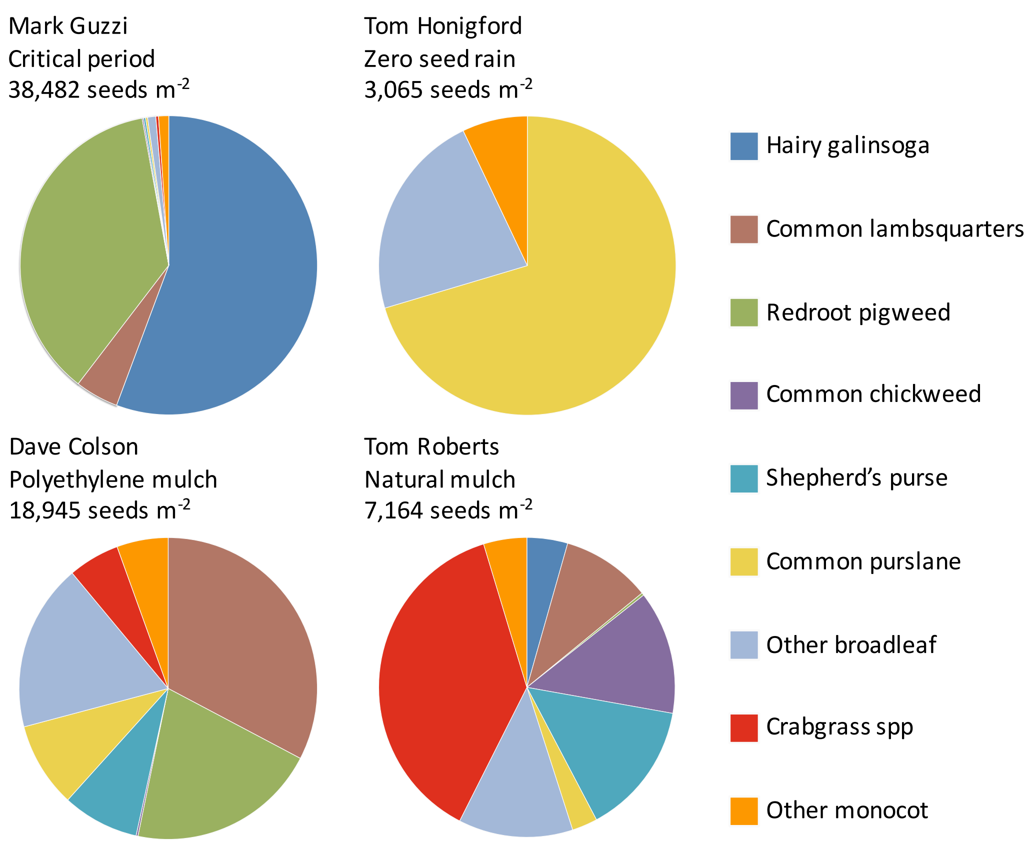
Weed Seedbank Data

Guzzi had the largest weed seedbank (38,482 seeds m^{-2}) (Figure 3.1.), which is as expected since critical period weed control often allows weeds to set seed (Norris 1999). Two competitive and fecund broadleaf weeds, hairy galinsoga and redroot pigweed (*Amaranthus retroflexus*) dominated his weed seedbank. Given Honigford's zero seed rain strategy, it follows that he had the lowest weed seedbank (3,065 seeds m^{-2}), the majority of which was common purslane, a species that was going to seed after it was pulled. Subtracting common purslane, Honigford's seedbank was extremely low, 736 seeds m^{-2}, which is similar to the 550 seeds m^{-2} at Eric and Anne Nordell's Beech Grove Farm (Gallandt unpublished). Colson's weed seedbank (18,945 seeds m^{-2}) reflects the effect of the mulch suppressing most weeds in the beds, but often allowing weeds in the paths to go to seed. Roberts' seedbank was surprisingly low (7,164 seed m^{-2}), perhaps demonstrating the effectiveness of his mulching and his timing of hay mulch harvest to prevent weed seed contamination. Overall, despite each farmer demonstrating in-depth knowledge of the weed seedbank, seedbank densities varied widely. Similarly, farmer knowledge was not the limiting factor in predicting successful weed management in the Midwest (Zwickle 2011), but emphasis on long-term management was inversely related to abundance of particularly pernicious weeds species on farms in northern New England (Jabbour et al. 2014b).

Soil Organic Matter

SOM at Guzzi's farm was 6.0%, which is on the high end of typical northern New England organic vegetable farms. Honigford had the lowest SOM at 3.8%, possibly related to his more coarsely textured soil, frequent cultivation, and twice-annual tillage. Colson's SOM was 4.8%. Roberts had the highest SOM, at 21.0%, reflecting his regular application of natural mulch. A sample taken from the no-till perennial crops of Roberts had soil organic matter of 30.5%.

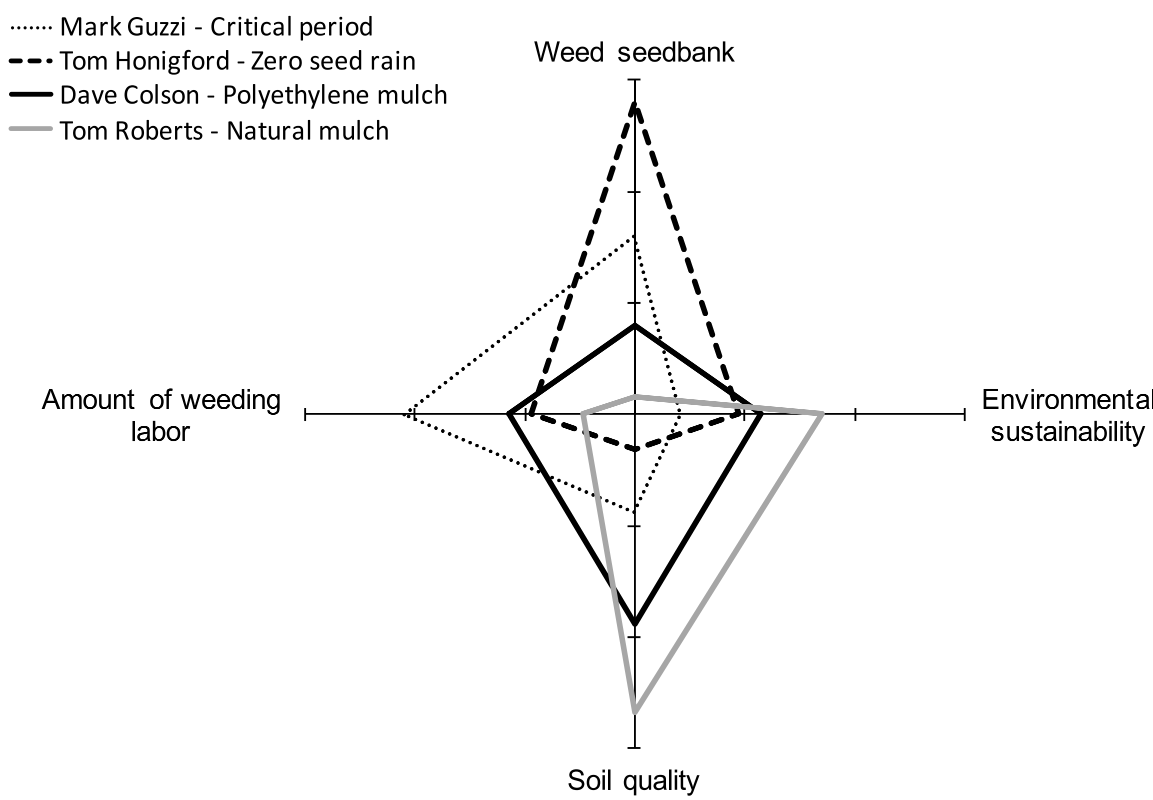
Figure 3.1. Weed species composition determined from germinable seedbank assays of soil samples from each participating farmer. Listed below each farmer's name is the weed management strategy that they represent and their total weed seedbank density.



Importance of Criteria Related to Management

Based on ranking of pairwise comparisons of criteria related to management, Guzzi placed most emphasis on the amount of weeding labor of his operation (Figure 3.2.) – this aligns with the ability of critical period weed control to maximize yield while minimizing in-season control efforts (Knezevic et al. 2002). The weed seedbank was also valued highly by Guzzi, although this may represent a more recent change in his priorities. Honigford placed the most importance on the weed seedbank, which provides insight into his rationale for frequent cultivation. Colson was highly balanced in his valuations, which was also demonstrated in interview, “there is always this juggling act between cutting down on the weeds, …planning [crop rotation], and keeping an eye on soil fertility and soil health at the same time.” Finally, Roberts was most concerned with soil quality, followed by environmental sustainability of his farm. His use of natural mulch satisfies both those concerns since the mulch likely improves soil organic matter and provides much of his fertility, mostly from his own low-input haying operation rather than purchasing fertility from an outside source. Interestingly, he did not place great importance on the weed seedbank, possibly because his mulch suppresses weed emergence regardless of density. This indicates that his low weed seedbank (Figure 3.1.), is an unintended benefit of the natural mulch.

Figure 3.2. Radar plot of the importance of four criteria related to management to case study farmers representing each weed management strategy. Values were derived by normalizing pairwise comparison rankings of all four criteria by each farmer.



Likelihood of Adhering to Current Strategy Under Different Circumstances

When asked about how his strategy would change if he was given land with a lower weed seedbank, Guzzi spoke of what has happened thus far when he has been in that situation in using surrounding hayfields to grow vegetables. He mentioned that the peripheral location of these extra fields means there are fewer, less intensive crops that he will grow there. They are crops that can yield well with minimal weeding. Growing these crops likely increases the weed seedbank but he can cover crop or fallow that land for subsequent years to bring the seedbank back down (*in sensu* Mirsky et al. 2010). Guzzi is also moving toward more of a mulch-based system for many of his crops, which seems to be an effective way to suppress emergence from the sizable seedbank. He is also removing winter squash from the rotation in the weedier fields at his home farm because "You can get a great crop and still have weeds going to seed, so the incentive to go out there and [weed] is low but the effect on subsequent crops is high." Contrastingly, Honigford already has a low seedbank and is satisfied with his current strategy, thus we asked if he would return to the same strategy if he was forced to start over with a large seedbank. He responded "I'd go right back…to kill[ing] those weeds…it will pay off down the road." Colson indicated that he would continue using PE mulch even if his weed seedbank was very low. He also indicated that the PE benefits his sandy loam (Table 3.1.) soil by improving water retention. Likewise, Roberts would also continue using his natural mulch even if his soil had a near-zero weed seedbank. He explained,

> *"It's not just a weed suppressor, it's about keeping the water in the soil… if you don't use mulch you are in fact mulching with the top inch of soil because it dries to the extent that plants cannot use the nutrients. The fungal hyphae that are feeding the plant roots can't grow in it. So when mulching, suddenly the soil is an inch deeper because plants can use that top layer…You have this moist soil breaking down the*

organic matter of the mulch. Sometimes, I'll pull the mulch aside and find tomato roots right at the surface loving that initial decomposition of organic matter.

Roberts added that conditions are often sufficiently weed-free to transplant into overwintered mulch that was not incorporated, perhaps allowing for a no-till system. However, for small, direct-seeded crops like carrots or beets, he still uses primary and secondary tillage to prepare a fine seedbed.

Farmers tend to emphasize labor costs as the main economic risk of weeds (Jabbour et al. 2014a). Therefore, many are drawn to the idea of only controlling weeds during the critical period. Unfortunately, critical period weed control may result in a weed seedbank so large that shifting to a preventative strategy may seem overwhelming. Guzzi recognizes that he should have reduced the weed seedbank while his operation was small, but to try to reduce it now with cover crops and bare fallow periods would require him to scale back his operation, which he is reluctant to do. Guzzi was the only farmer that is shifting to a different strategy. Whereas Honigford, who is on the other end of the weed tolerance spectrum, was the only farmer to mention the ample profitability of their operation. Part of Honigford's profitability relates to his ability to farm four hectares of vegetables with only two additional workers. His low weed emergence is a key factor that allows him to persist with low labor costs. Roberts also had a low weed seedbank but the labor necessary to apply the mulch requires him to employ a larger crew.

Overall, concepts presented by case study farmers aligned with a systems comparison of the different strategies conducted by Brown and Gallandt (in review). In this related study conducted in yellow onion, we found that critical period weed control required the least labor but greatly increased the weed seedbank, the extra weeding cost required for a zero seed rain approach was overcome by increased yield, PE mulching warmed the soil and reduced nitrate loss, hay mulching required the most labor but performed best in a variety of measures of soil health.

The farmer experiences presented in these case studies should allow for more informed decisions of how to invest in weed management. While we have investigated each strategy separately, many farmers incorporate successful aspects of each strategy into their management. One common example is the use of natural mulch to suppress weeds in the pathways between PE mulch. Applying natural mulch to the paths would be quicker than carefully mulching in the crop beds. A zero seed rain approach could perhaps be combined with mulching in order benefit from the soil improving aspects of the mulch while reducing the weed seedbank. Indeed, there is no “best” weed management strategy, but rather, tradeoffs between reducing management costs while improving soil health and decreasing the weed seedbank.

CHAPTER 4

EVIDENCE OF SYNERGY WITH "STACKED" INTRA-ROW CULTIVATION TOOLS

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Chapter Abstract

Intra-row cultivation efficacy is typically low and highly variable. Since the mechanisms affecting weed mortality likely vary by tool, several companies have developed cultivators with the ability to use multiple different intra-row tools at once. We evaluated the potential for such "stacking" of cultivation tools to increase efficacy. We used different sequences of torsion weeders, finger weeders, and row harrows in a test crop of maize with surrogate weeds, white mustard (*Sinapsis alba*) and white proso millet (*Panicum miliaceum*). Most tool combinations resulted in an additive increase in efficacy. However, the combination of torsion-finger-row harrow demonstrated a synergistic increase in efficacy compared to the individual tools. Forward speed, soil moisture, and weed size were negatively correlated with efficacy, but the torsion-finger-row harrow combination continued to demonstrate a synergistic increase in efficacy compared to the individual tools in 7 of 11 cases. The drawback was high crop mortality (16.0 ± 1.16%). However, it is likely that further research will reduce crop mortality through tool adjustment or cultural factors.

Introduction

Weeds in the intra-row zone are typically undisturbed by inter-row cultivation (Vanhala et al. 2004) and only moderately controlled by intra-row tools (Gallandt et al. 2017). Although uncontrolled weeds in the intra-row zone may cause yield losses (Ascard and Fogelberg 2008), lack of adequate herbicides for some crops, combined with prohibitively expensive hand-weeding, suggest that improving intra-row cultivation may be the best option forward (Fennimore et al*.* 2016).

Intra-row cultivation tools such as torsion weeders, finger weeders, and harrows, are less aggressive than inter-row tools in order to minimize crop damage. Tool aggressiveness must be further lessened to avoid damaging young crops (Rasmussen et al*.* 2010) by allowing a wider space between tools (Van Der Schans et al. 2006) or by decreasing forward speed (Rasmussen 1992). Indeed, selectivity, or the ratio of weed control efficacy to crop damage, is often improved by decreasing forward speed (Rasmussen 1992). Conversely, increased forward speed of spring tine harrowing operations has been linked to increased efficacy (Rydberg 1994) possibly due to increased weed uprooting (Kurstjens et al*.* 2000), increased soil movement (Kouwenhoven and Terpstra 1979), or increased plant bending that results in more burial (Kurstjens and Perdok 2000). Soil moisture may also impact cultivation efficacy. Cultivation is typically less effective in wet conditions (Kurstjens and Perdok 2000), possibly due to increased likelihood of re-rooting (Terpstra and Kouwenhoven 1981). Weed size is another important factor. Efficacy of intra-row tools is very low for large weeds (Kurstjens and Perdok 2000), reflecting low aggressiveness of intra-row tools as well as the increased anchorage forces (Kurstjens and Kropff 2004) and resource reserves of larger plants. Indeed, there is a large increase in survival as plants grow beyond the cotyledon stage (Kurstjens et al*.* 2000).

To address the low efficacy and high sensitivity of intra-row tools, recent innovation has focused on “intelligent” guidance-system technology (Fennimore et al. 2016; Van Der Weide et al. 2008). However, advanced guidance technologies may not exceed the performance of much simpler cultivation tools (Melander et al. 2015). One recent innovation with the simpler tools is “stacking” multiple different intra-row tools on the same cultivator (see haknl.com, steketee.com, neu.kresslandtechnik.de). Since different tools use different mechanisms to achieve weed mortality, including severing (Mohler 2001), uprooting (Kurstjens et al. 2000), and burial (Baerveldt and Ascard 1999; Kurstjens and Kropff 2000), perhaps using multiple different tools in the same pass could ensure consistently higher efficacy. We hypothesized that certain combinations of different intra-row tools would interact in a synergistic manner to achieve high efficacy over a range of conditions. We tested combinations of torsion weeders, finger weeders, and harrows and evaluated synergy using methods typically used in herbicide research (Colby 1967; Walsh et al. 2012). The most effective combination of tools was then evaluated over ranges of tractor forward speed, soil moisture, and weed size.

Materials and Methods

Experimental Setup

Efficacy of intra-row cultivation tools was evaluated in field experiments in 2016 at the University of Maine Rogers Farm in Old Town, ME (44.93°N, 68.70°W). Each experiment was replicated on two fields, Field E and Field Q, composed of Nicholville very fine sandy loam and Elmwood fine sandy loam, respectively. Maize (*Zea mays* L. cv Wapsie Valley, FedCo Seeds, Clinton, ME) was used as the test crop and white mustard (*Sinapsis alba* L.) (Johnny's Selected Seeds, Winslow, ME) and white proso millet (*Panicum miliaceum* L.) (Hancock Seed Company, Dade City, FL) were used as surrogate weeds (Kurstjens and Kropff 2004; Kolb et al. 2010). All tractor operations were conducted using a John Deere 6200 (Deere and Company, Moline, IL) with a 1.7 m on-center wheelbase. Primary and secondary tillage were achieved with a 3-m rototiller (Kuhn EL62, Saverne, France) and a 3 m field cultivator (Rigid Perfecta II Harrow, Unverferth Manufacturing Co. Inc., Kalida, OH), respectively. Maize was seeded at 72,000 seeds ha^{-1} in rows 81 cm apart using a John Deere 7000 4-row planter (Deere and Company, Moline, IL). Only the two center rows were planted since a two-row cultivator would be used (Mohler 2001). For each tractor pass with the planter, tire tracks did not overlap. This was done to minimize traffic, which could potentially affect efficacy. Due to the short duration of experiments, no fertility was applied.

Treatments were arranged in a randomized complete block design with four replicates. Plots were 4.0 m long by 0.5 m wide, centered on single rows of maize. There was a 2 m buffer on either end of each plot. In each plot, 3,000 seeds m^{-2} (Olsen et al. 2005) of either mustard or millet were broadcast by hand, with the aim of at least 100 seedlings $quadrat^{-1}$ (Vanhala et al. 2004). Immediately prior to broadcasting, seeds were soaked in water for 1 h to encourage rapid and uniform emergence. Plots were raked by hand immediately following seeding.

Since monocotyledon crops may be harrowed prior to emergence (Lundkvist 2009), seeding of surrogate weeds occurred at the time of crop emergence (Appendix S1). This allowed the surrogate weeds to be in the cotyledon stage during the timeframe of an early post-emergence cultivation, when the maize had 2–3 leaves, 5–7 d after crop emergence. In the initial two trials, both surrogate weeds were planted on the same date, however, since millet did not emerge prior to cultivation, it was subsequently planted 2–3 d prior to mustard (Appendix S1).

Pre-cultivation censuses of surrogate weeds were completed immediately prior to cultivation and post-cultivation censuses were conducted 24–48 h after cultivation, which allowed sufficient time for desiccation or re-rooting (Evans et al. 2012; Mohler et al. 2016). Censuses were conducted by placing a 100-cm long by 10-cm wide quadrat in the center of each plot, centered lengthwise over the 10 cm intra-row zone (Vanhala et al. 2004). Quadrats also delineated an inner 5-cm zone. Pre-cultivation quadrat locations were marked with flags so that the location could be revisited in post-cultivation censuses. Censuses were conducted with photographs so that all plots could be evaluated in a timely manner. Each quadrat was photographed from a height of 1.5 m with a Canon EOS 20D (Canon, Inc., Tokyo, Japan), at a zero-degree camera angle, using the highest image quality setting, 3504 by 2336 pixels. Photographs were later viewed on a computer screen and the number of surrogate weeds in each section of the quadrat was counted. Ambient weeds were nearly absent and were ignored. The young maize crop was estimated to have obscured less than 3% of the surrogate weeds per quadrat. Thus, the accuracy of this technique matched similar methods (Rasmussen et al*.* 2007). Crop mortality was assessed by counting the total pre- and post-cultivation maize plants per plot. Soil moisture of the top 8 cm of soil was measured immediately prior to cultivation using a Delta-T HH2 Moisture Meter with a Theta Probe (Delta-T Devices, Burwell, UK).

Cultivation was conducted with a HAK S-Series two-row cultivator (HAK Schoffeltechniek, Moerkapelle Holland), which has the potential to utilize different tools in multiple possible sequences. Tools included a torsion weeder, a finger weeder, and a row harrow, which is similar to a spring tine harrow, but utilizes a weight for downward pressure. A 3-m spring tine harrow (Lely Industries NV, Series 982, Type 3, Maasland, Holland) was used for a reference treatment in all experiments. Cultivation occurred mid-day, after morning crop turgidity, which can increase crop injury (Rathers and Harrison 1951), had subsided. All cultivation occurred in sunny conditions with the exception of trials on 10 June and 16 August. Daily maximum temperatures and mean soil moisture are presented in Table 4.1. Unless otherwise noted, tractor forward speed for the HAK cultivator was 4.8 km h^{-1} and forward speed for the spring tine harrow was 11.2 km hr^{-1}.

Table 4.1. Field conditions for experiments conducted in 2016 comparing efficacy of intra-row cultivation tools. Air temperature data is from www.ncdc.noaa.gov. Soil moisture values (±SE) are for very dry, dry, moist, and wet conditions.

Experiment	Field	Date	Soil moisture level	Daily maximum air temperature	Mean volumetric soil moisture
				C	%
Screening	E	2 Jun	–	19	17 ± 0.2
	Q	10 Jun	–	18	23 ± 0.2
Forward speed	E	1 Jul	–	29	19 ± 0.8
	Q	25 Jul	–	28	12 ± 0.3
Soil moisture	E	2 Aug	Very dry	27	13 ± 0.3
			Dry		16 ± 0.3
			Moist		17 ± 0.2
			Wet		22 ± 0.4
	Q	16 Aug	Very dry	26	13 ± 0.2
			Dry		14 ± 0.2
			Moist		16 ± 0.3
			Wet		20 ± 0.3
Weed size	E	25 Aug	–	28	15 ± 0.6
	Q	13 Sep	–	27	13 ± 0.2

The two-row HAK cultivator could utilize a different sequence of tools for each row. Thus, two treatments were implemented in side-by-side plots. These plots were in relatively close proximity, but the tools were operating primarily in the 10 cm intra-row band, and 81 cm row spacing provided ample space between treatments. Indeed, tools of Evans et al. (2012) were likely in closer proximity and no cross contamination of effects between cultivation tools was observed in their experiments.

To qualitatively evaluate the mechanisms of action of the cultivation tools, GoPro 4 Hero Silver video cameras (GoPro, San Mateo, CA) were mounted on each tool arm, 45 cm from the ground, and set to record in 720p, 120 frames per second.

Treatments

To assess the potential for synergy between cultivation tools, each of the HAK implements was used singly and in all feasible combinations of two and three tools (Table 4.2.). In all, there were 16 treatments, which were employed once per block. Tool adjustment is critical to performance (Van Der Schans et al. 2006). Therefore, we conducted preliminary field experiments in which tools were observed and adjusted over the course of the previous field season. Torsion weeder tips were angled downward at 10 degrees and set 1 cm apart; further spreading of the tips would occur in use. Depth-gauge wheels were set so that the torsion tips operated 1–3 cm below the soil surface. Finger weeders were suspended nearly vertically from the tool arm, but with a 3-degree backward tilt when in operation, causing some hilling of soil. Tips of fingers were 1 cm apart. The row harrow was set so that all tine tips contacted the soil and the counter weight was at the most aggressive setting. The tool arm for the finger weeder and row harrow was set to exert maximum downward pressure on the tools. The tool arm was 5-degrees above level when in operation, and the height of the finger weeder and row harrow were adjusted between 51 and 55 cm, depending on the tool combination. The spring tine harrow was operated with uncompressed tines at an angle of 10 degrees back from vertical, which resulted in compressed tines operating at 60 degrees back from vertical.

The best-performing stacked combination of tools from the screening experiment was compared to the individual tools and the spring tine harrow in separate experiments that varied either tractor forward speed, soil moisture, and weed size. In the two trials varying forward speed, speeds included 1.6, 4.8, 8.0, and 11.2 km hr^{-1}, covering the range of possible cultivation speed (Vanhala et al. 2004). Cultivators were held in a raised position as tractor speed increased and were lowered to engage with the soil as they entered the buffer zone in front of each plot.

In the two trials examining soil moisture, we created an orthogonal design of very dry, dry, moist, and wet conditions. In otherwise dry conditions, very dry conditions were created in Field E by covering select plots with tarps during a nighttime rain of 22 mm that occurred 5 d prior to cultivation. Field Q was covered for a nighttime rain of 14 mm that occurred 3 d prior to cultivation. One hour prior to cultivation, moist and wet plots were irrigated by hand using a hose sprayer for 30 and 60 s each, simulating 10 and 20 mm of precipitation, respectively. Prior to cultivation, soil moisture measurements were conducted as previously described.

In two final trials, weed size was manipulated by seeding surrogate weeds an average of 8, 13, and 18 d in advance of cultivation (Appendix S1) to produce cohorts in the cotyledon, 2-, and 4-leaf stages, respectively. Several hours prior to cultivation, three representative surrogate weeds were clipped at ground level and placed in paper bags. Bags were placed in drying ovens for 1 wk at 46 C, and samples were weighed.

Calculations

Cultivation efficacy for each plot was calculated using the following equation:

$$\text{Efficacy (\%)} = 100 - (S_p \times 100) / S_u \qquad \text{(Equation 4.1.)}$$

where S_q is the percent survival of surrogate weeds in each quadrat and S_u is the mean percent survival of surrogate weeds in the un-cultivated control plots. The S_u term was used to correct for new emergence or mortality not caused by cultivation. In experiments varying soil moisture or weed size, S_u was calculated based on soil moisture or weed size cohorts to correct for possible differences between cohorts.

To evaluate potential for synergy between stacked cultivation tools, the observed efficacy of each tool combination was compared to the efficacy expected, given an additive relationship between tools. The method of Colby (1967) was adapted to calculate expected efficacy, for combinations of two tools:

Expected efficacy (%) = 1 – (X × Y) / 100 (Equation 4.2.)

or three tools:

Expected efficacy (%) = 1 – (X × Y × Z) / 10,000 (Equation 4.3.)

where X is the mean surrogate weed survival of the first tool used individually, Y is the mean surrogate weed survival of the second tool used individually, and Z is the mean surrogate weed survival of the third tool used individually.

Selectivity is typically the ratio between weed control and crop damage (Gallandt et al. 2017). Thus, we calculated selectivity for each cultivation tool as:

Selectivity = Efficacy (%) / Crop mortality (%) (Equation 4.4.)

However, since selectivity ratios may favor cultivation tools with low efficacy (Rasmussen, 1992), the crop mortality associated with the number of cultivation passes (N) required to achieve 80% weed control (Rasmussen et al. 2010) was also calculated. This was done by rearranging the method of Colby (1967) to form:

$N = \ln (S_f / 100) / (\ln (S_m) - \ln 100)$ (Equation 4.5.)

where S_f is the final percent survival of surrogate weeds (in this case 20%) and S_m is the percent survival achieved with a single pass of a given tool. The number of cultivation passes was used to calculate the associated crop damage with another variation of the method of Colby (1967):

Total crop mortality (%) = $100 - (100 \times (S_c^N / 100^N)$ (Equation 4.6.)

where S_c is the mean percent survival of the crop for a given tool.

Statistical analyses were completed in JMP 10 (SAS Institute Inc., Cary, NC). The two screening trials were combined due to lack of interaction of tool by field ($F_{13,82} = 1.17$, $P = 0.318$). Expected efficacy of each tool combination was compared to the observed efficacy in two-tailed, one-sample t-tests, following Walsh *et al*. (2012). Combinations with efficacy significantly greater or less than the expected efficacy were considered synergistic or antagonistic, all others were considered additive. Effects of cultivation tool and conditions on efficacy and crop mortality were evaluated with ANOVA. In experiments manipulating forward speed, soil moisture, and weed size, the continuous variables of speed, volumetric soil moisture, and aboveground dry mass of surrogate weeds were used in analyses. Assumptions of normality, constant variance, and independence of errors for t-tests and ANOVA were evaluated visually with q-q plots and residual by fitted plots. Data were transformed as necessary. A significance level of 0.05 was used throughout the study. When soil moisture was experimentally manipulated, millet did not emerge in time for cultivation on Field Q, thus ANOVA was conducted by species. In the weed size experiment, the cotyledon cohort on Field Q was excluded due to sampling error, thus, ANOVA was conducted by field.

Results and Discussion

Screening of Tool Combinations

Efficacy ranged from 19 to 75% in the screening trials of different intra-row cultivation tool combinations (Table 4.2.). The individual tools performed similarly to a spring tine harrow ($F_{1,36} = 0.63$, $P = 0.431$). However, efficacy was greater for the two- and three-tool combinations ($F_{1,69} = 13.83$, $P < 0.001$ and $F_{1,35} = 44.46$, $P < 0.001$, respectively). Assuming an additive interaction between individual tools, the expected efficacy of two-tool combinations was calculated as 43% on average, whereas the expected three-tool efficacy was 57%. Most of the tool combinations performed no different than expected based on an additive relationship and none of the combinations were antagonistic (Table 4.2.). However, the observed efficacy of the torsion-finger-row harrow combination was greater than expected, indicating a synergistic interaction between tools.

Table 4.2. Screening of efficacy (±SE) of different sequences of intra-row cultivation tools for potential synergy. Data combined over two screening trials. Expected values were based on the efficacy of the individual tools, following Colby (1967). The difference between observed and expected values was evaluated in a two-tailed, one-sample t-test (Walsh et al. 2012).

Tool	Efficacy		Difference between expected and observed	Combined effect
	Expected	Observed		
	%		P	
Spring tine harrow	–	19 ± 5.3	–	–
Finger	–	23 ± 6.9	–	–
Row harrow	–	26 ± 5.1	–	–
Torsion	–	24 ± 6.9	–	–
Finger-Finger	41	39 ± 7.6	0.803	Additive
Finger-Row harrow	43	37 ± 7.9	0.467	Additive
Row harrow-Finger	43	36 ± 5.5	0.207	Additive
Row harrow-Row harrow	45	35 ± 10.1	0.367	Additive
Row harrow-Torsion	44	43 ± 12.4	0.953	Additive
Torsion-Finger	42	48 ± 7.8	0.470	Additive
Torsion-Row harrow	44	56 ± 8.7	0.209	Additive
Torsion-Torsion	43	33 ± 12.1	0.453	Additive
Row harrow-Torsion-Finger	57	57 ± 6.7	0.999	Additive
Torsion-Finger-Row harrow	57	75 ± 5.1	0.010	Synergistic
Torsion-Row harrow-Finger	57	65 ± 5.5	0.202	Additive

Slow-motion video of the torsion-finger-row harrow combination indicates that the torsion weeder undercut weeds and loosened soil on either side of the crop row, which allowed the finger weeders to more effectively penetrate the soil and uproot weeds in the inner intra-row zone. Finally, the loosened soil allowed the row harrow to bury remaining weeds.

Effects of Conditions

In separate experiments that varied forward speed, soil moisture, and weed size, the torsion-finger-row harrow combination never demonstrated antagonism, additivity was exhibited in 4 of 11 examples, and in the remaining 7 cases, synergy was observed compared to the individual tools (Table 4.3.).

Table 4.3. Evaluation of synergy in efficacy (±SE) of a torsion-finger-row harrow combination of intra-row cultivation tools in experiments varying forward speed, soil moisture, and weed size. Expected values were based on the efficacy of the individual tools, following Colby (1967). The difference between observed and expected values was evaluated in a two-tailed, one-sample t-test (Walsh et al. 2012).

Experiment	Field	Surrogate weed species	Efficacy		Difference between expected and observed (P)	Combined effect
			Expected	Observed		
			%		P	
Forward speed	E	Mustard	67	76 ± 4.8	0.017	Synergistic
		Millet	92	71 ± 11.0	0.109	Additive
	Q	Mustard	66	63 ± 2.6	0.353	Additive
		Millet	68	82 ± 2.1	<0.001	Synergistic
Soil moisture	E	Mustard	72	87 ± 2.2	<0.001	Synergistic
		Millet	73	78 ± 5.7	0.085	Additive
	Q	Mustard	12	44 ± 3.4	<0.001	Synergistic
Weed Size	E	Mustard	49	61 ± 6.8	0.045	Synergistic
		Millet	78	86 ± 3.1	0.010	Synergistic
	Q	Mustard	56	65 ± 7.6	0.146	Additive
		Millet	73	88 ± 4.8	0.004	Synergistic

In the experiment evaluating forward speed, efficacy was affected by tool, forward speed, surrogate weed species, and field (Table 4.4.). Efficacy generally decreased with increasing forward speed and remained greatest for the torsion-finger-row harrow combination (Figure 4.1.A). Efficacy was 12% greater for millet than mustard and 11% greater for Field E than Field Q. The only interaction was between tool and species, resulting from finger weeder efficacy increasing from 26 ± 4.3 for mustard to 57 ± 4.8 for millet.

Figure 4.1. Cultivation efficacy of intra-row tools in three separate experiments in which (A) forward speed, (B) soil moisture, and (C) weed size were manipulated, respectively. Intra-row tools included a spring tine harrow, torsion weeder, finger weeder, row harrow, and a torsion-finger-row harrow combination. The grey band represents the 95% confidence interval. Data represented in A and C was combined over two surrogate weed species and two fields. Only data for Field E is presented in B.

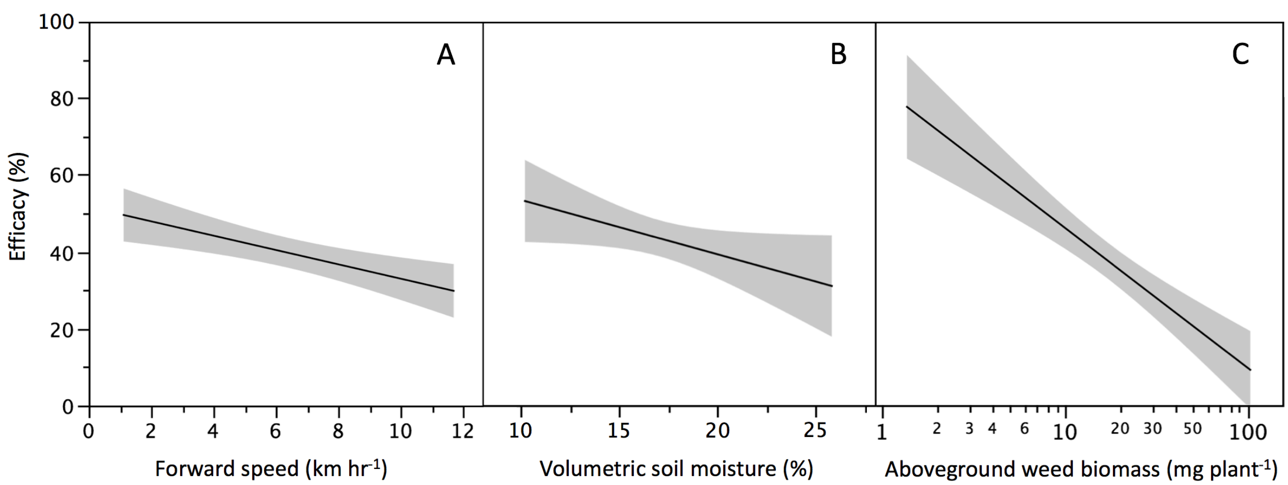

Table 4.4. ANOVA of cultivation efficacy for several intra-row tools as forward speed varied. Efficacy was square root transformed to satisfy assumptions of ANOVA. Tools included a spring tine harrow, torsion weeder, finger weeder, row harrow, and a torsion-finger-row harrow combination. Forward speed varied from 1.6 to 11.2 km h^{-1}. Two species of surrogate weeds were used, white mustard and white proso millet. The experiment was replicated on two fields.

ANOVA source	df	F	P
Tool	4	44.5	<0.001
Speed	1	11.4	0.001
Species	1	14.1	<0.001
Field	1	8.7	0.004
Tool × Speed	4	0.5	0.736
Tool × Species	4	3.7	0.006
Tool × Field	4	1.5	0.207
Speed × Species	1	2.4	0.126
Speed × Field	1	2.0	0.162
Tool × Speed × Species	4	1.4	0.250
Tool × Speed × Field	4	0.7	0.607

When soil moisture was varied, cultivation efficacy was affected by tool and soil moisture (Table 4.5.). Overall, increasing soil moisture had a negative effect on efficacy (Figure 4.1.B). For mustard, the interaction of tool and field (Table 4.5.) relates to efficacy being 67% less on Field Q, however, the reduction was less severe for the spring tine harrow than the other tools (data not shown).

Table 4.5. ANOVA of cultivation efficacy of several intra-row tools as soil moisture varied. Efficacy was evaluated using surrogate weeds, white mustard and white proso millet. Tools included a spring tine harrow, torsion weeder, finger weeder, row harrow, and a torsion-finger-row harrow combination. Soil moisture ranged from 10.9 to 25.1%. The experiment was replicated on two fields. Millet was only evaluated on Field E. Efficacy was square root transformed to satisfy assumptions of ANOVA.

ANOVA source	White mustard			White proso millet		
	df	F	P	df	F	P
Tool	4	61.3	<0.001	4	20.6	<0.001
Moisture	1	4.0	0.046	1	13.4	0.001
Field	1	130.4	<0.001	–	–	–
Tool × Moisture	4	1.1	0.381	4	0.9	0.490
Tool × Field	4	12.3	<0.001	–	–	–
Moisture × Field	1	0.0	0.935	–	–	–
Tool × Moisture × Field	4	0.8	0.525	–	–	–

Over a range of weed sizes, efficacy varied significantly by cultivation tool and aboveground dry mass of surrogate weeds (Table 4.6.). Efficacy decreased with increasing weed size (Figure 4.1.C). In Field Q, there were several significant treatment interactions (Table 4.6.). Efficacy was 39% less for Mustard compared to millet, but the torsion weeder, finger weeder, and row harrow performed equally with both species ($F_{1,16}$ = 0.52, P = 0.451; $F_{1,16}$ = 1.0, P = 0.329, and $F_{1,16}$ = 0.0, P = 0.930, respectively). Efficacy declined with increasing weed biomass for mustard ($F_{1,42}$ = 10.13, P = 0.003) but not for Millet ($F_{1,42}$ = 0.34, P = 0.573). Finally, for mustard, most of the tools were negatively affected by increasing aboveground surrogate weed mass, however, for millet, none of the tools were affected (data not shown). The interactions in Field Q may relate to the 62% smaller range of millet aboveground dry mass compared to mustard.

Table 4.6. ANOVA of cultivation efficacy in two field trials for several intra-row tools as aboveground dry mass per plant (Mass) varied. Tools included a spring tine harrow, torsion weeder, finger weeder, row harrow, and a torsion-finger-row harrow combination. Mass varied from 1.7 to 114.6 mg plant^{-1} and values were log transformed following results of Kurstjens et al. (2000). Two species of surrogate weeds were used, white mustard and white proso millet.

ANOVA source		Field E		Field Q	
	df	F	P	F	P
Tool	4	4.1	0.005	38.0	<0.001
Mass	1	4.8	0.032	34.4	<0.001
Species	1	0.0	0.946	10.8	0.001
Tool × Mass	4	1.8	0.148	2.2	0.073
Tool × Species	4	2.0	0.098	2.9	0.026
Mass × Species	1	2.4	0.129	14.1	<0.001
Tool × Mass × Species	4	0.3	0.871	4.4	0.002

Over all experiments, efficacy was greater in the two outer 2.5 cm zones than the inner 5 cm of the intra-row region (paired t_{815} = 2.30, P = 0.022), and there was no tool by zone interaction for this effect ($F_{4,1635}$ = 1.01, P = 0.399).

Selectivity

Crop mortality of the torsion-finger-row harrow combination was 80% greater than for the individual tools (Table 4.7.). Crop mortality was affected by cultivation tool and forward speed, but not soil moisture (Table 4.8.). For every 1 km h^{-1} increase in forward speed, crop mortality increased 0.4%.

Table 4.7. Comparison of crop mortality (±SE) and weed control efficacy (±SE) of several intra-row cultivation tools. Tools included a spring tine harrow, torsion weeder, finger weeder, row harrow, and a torsion-finger-row harrow combination. Results are means of several experiments. Selectivity was determined by dividing efficacy by crop mortality. The number of passes required to achieve 80% weed control and the associated crop mortality were calculated using variations of the method of Colby (1967). The maize crop was in the 2–3 leaf stage, while the surrogate weeds, white mustard and white proso millet were in the cotyledon stage.

Tool	Crop mortality	Weed control efficacy	Selectivity ratio	Estimated passes to achieve 80% efficacy	Estimated crop mortality at 80% efficacy
	%	%		no.	%
Spring tine harrow	1.7 ± 0.50	22 ± 2.6	13	6.6	11
Torsion	8.9 ± 0.98	37 ± 2.5	4	3.5	28
Finger	1.0 ± 0.29	34 ± 2.6	34	3.8	4
Row harrow	1.5 ± 0.37	18 ± 2.6	12	8.0	12
Torsion-Finger-Row harrow	16.0 ± 1.16	71 ± 2.6	4	1.3	20

Efficacy of the torsion-finger-row harrow combination was 61% greater than the individual tools (Table 4.7.). However, selectivity was 75% less than the average selectivity of the individual tools. An alternative measure of selectivity was used to estimate crop mortality for each tool given the same 80% level of weed control (Table 4.7.). Using this technique, the torsion-finger-row harrow combination was estimated to require the fewest passes and incur 69% more crop mortality than the average of the individual tools.

Table 4.8. ANOVA of crop mortality for several intra-row cultivation tools in experiments in which forward speed and soil moisture were varied. Tools included a spring tine harrow, torsion weeder, finger weeder, row harrow, and a torsion-finger-row harrow combination. Forward speed varied from 1.6–11.2 km h^{-1}. Soil moisture ranged from 10.9–25.1%.

Experiment	Source	df	F	P
Forward Speed	Tool	4	16.2	<0.001
	Speed	1	5.0	0.027
	Field	1	7.0	0.009
	Tool × Speed	4	1.2	0.301
	Tool × Field	4	0.5	0.751
	Speed × Field	1	0.1	0.717
	Tool × Speed × Field	4	0.7	0.580
Soil Moisture	Tool	4	27.5	<0.001
	Moisture	1	3.3	0.073
	Field	1	0.8	0.381
	Tool × Moisture	4	0.6	0.643
	Tool × Field	4	1.1	0.356
	Moisture × Field	1	0.7	0.389
	Tool × Moisture × Field	4	0.5	0.741

Comparison of Results to Previous Research

To our knowledge, the stacked combination of torsion-finger-row harrow demonstrated the first evidence of synergy between cultivation tools. To the credit of the manufacturer, this particular sequence was their intended design. In assessing the forces influencing the synergy, slow-motion video indicates the three mechanisms of weed mortality, severing, uprooting, and burial (Evans et al. 2012; Kurstjens et al. 2000; Terpstra and Kouwenhoven 1981) were accomplished by the torsion, finger, and row harrow respectively. Additionally, the finger weeders and row harrow benefited from the previously disturbed soil. However, the similar torsion-row harrow-finger combination was not as effective, possibly because the soil was not as loosened for the row harrow, or because the finger weeder uncovered weeds that had been buried by the row harrow. Thus, perhaps the order of undercutting, followed by uprooting, followed by burial, is most effective. The effect of synergy between this stacked combination of tools was relatively robust to a range of tractor forward speeds, soil moisture levels, and weed sizes (Table 4.3.), which may perhaps widen the currently narrow range of conditions necessary for successful cultivation (Mohler 2001). The other stacked combinations demonstrated an additive increase in weed control efficacy (Table 4.2.), which may be less desirable than synergy, but demonstrates that farmers may generally improve weed control by adding tools to their cultivation setup, rather than making additional tractor passes.

The effects of conditions on cultivation efficacy (Figure 4.1.) generally aligned with previous literature, which has demonstrated negative effects of increasing soil moisture (Kurstjens and Perdok 2000; Mohler et al*.* 2016a) and weed size (Kurstjens et al*.* 2000; Pullen and Cowell 1997). Efficacy appeared to be most sensitive to changes in weed size (Figure 4.1.). Since white mustard and white proso millet are relatively large in the cotyledon stage, efficacy would likely be greater for many summer annual weeds. The negative correlation between efficacy and forward speed (Figure 4.1.A) was contrary to previous work (Kurstjens et al*.* 2000; Rasmussen 1992; Rydberg 1994). The row harrow and spring tine harrow may not have sufficiently penetrated the soil at higher speed. Additionally, the angled nature of the torsion weeder may have allowed the working ends to splay away from the crop at higher speed. Indeed, all tools were less effective in the inner area of the intra-row zone, possibly due to the design of the torsion weeder and finger weeder, or interference by the crop for the harrows (Rasmussen and Ascard 1995), and this effect may have increased at higher speed.

The high crop mortality of the torsion-finger-row harrow sequence (Table 4.7.) reflects the relatively high degree of soil disturbance by this combination. Crop mortality of the maize was especially high, given that monocotyledon crops are typically less sensitive to cultivation than dicotyledon crops (Rasmussen and Ascard 1995). To achieve 80% efficacy, the stacked combination was estimated to incur

20% crop mortality (Table 4.7.). Comparatively, Rasmussen et al. (2010) found that at 80% weed control, harrowing visually covered 23–33% of a spring barley crop with soil, but actual crop injury was likely insignificant since yield was minimally affected. Thus, selectivity of the stacked combination clearly needs to be improved. This could perhaps be achieved with tool adjustment. Tips of the torsion and finger weeders could be separated to allow more space for the crop to pass through. The tines of the row harrow could be less densely spaced and the downward pressure could be reduced. When these changes were implemented in an on-farm trial with dry beans (*Phaseolus vulgaris* L.), there was no crop mortality, and high efficacy was still achieved (B. Brown, unpublished data). Furthermore, crop cultivars could be selected based on cultivation tolerant traits (Gallandt et al. 2017), such as early-season vigor (Rasmussen and Rasmussen 2000), and for some crops, transplanting may be used to ensure an early size advantage for successful intra-row cultivation (Ascard and Fogelberg 2008).

In conclusion, the stacked, torsion-finger-row harrow combination demonstrated a synergistic increase in efficacy over a wide range of field conditions. Crop mortality was high; therefore, selectivity was preferable for some of the individual tools. However, crop mortality could be reduced through tool adjustment or cultural methods. We recommend that growers adopt stacked cultivation technology to improve efficacy of weed control in row crops.

CHAPTER 5

EMERGENCE PERIODICITY OF PROBLEM WEEDS IN NORTHEASTERN USA AND IMPLICATIONS FOR ECOLOGICALLY BASED MANAGEMENT

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Chapter Abstract

Increased knowledge of weed emergence periodicity has the potential to improve ecologically based management tactics. At sites in Maine, New Hampshire, and New York, we recorded emergence of ambient weeds, by species, resulting from a time series of tillage treatments at two-week intervals from late April through late September 2013. For most species, tillage dates resulting in maximum emergence were within the range of peak emergence dates previously reported from other temperate climates. These peak emergence periods may be used to improve implementation of weed management tactics such as the timing of stale seedbed periods, crop planting dates, cover cropping, weed suppression, mechanical cultivation, and herbicide use. Unfortunately, some of the most problematic

species exhibited protracted emergence, which may require extended control tactics as part of an herbicide resistance management and seedbank management approach.

Introduction

Improved understanding of weed biology and ecology is necessary to guide weed management (Mortensen et al. 2000). In particular, improved knowledge of weed emergence periodicity may be used to enhance management tactics (Bastiaans et al. 2008; Norsworthy et al. 2012) since the timing of weed emergence is among the most important variables determining how species respond to management (Ryan et al. 2010).

Species with similar emergence timelines may be targeted by altering the timing of tillage (Smith 2006). Furthermore, stale seedbed periods, which encourage weed germination prior to planting so that control of the resulting cohort effectively removes those individuals from the weed seedbank (Forcella et al. 1993; Lonsbary et al. 2003; Riemens et al. 2007), may be timed to target weeds with known emergence trends. Therefore, accurate prediction of emergence periodicity would allow for optimization of the timing of the stale seedbed to maximize germination, and thus, debits to the weed seedbank (Gallandt 2006, 2014). Since efficacy of mechanical (Evans et al. 2012; Gallant 2014) and chemical controls (Dieleman et al. 1999) is density independent, a reduced initial weed density – as provided by stale seedbed periods – is critical to their success (Hartzler and Roth 1993; Mortensen et al. 1993).

Emergence periodicity could also inform crop rotation and corresponding planting date decisons so that peak emergence periods do not coincide with critical crop growing periods (Knezevic et al. 2002). Management decisions related to in-season competition could also be improved from enhanced knowledge of emergence periodicity. Furthermore, timing of emergence is critical to the success of both mechanical and chemical control (Forcella 1999). Therefore, to improve management, modeling efforts have attempted to predict emergence based on temperature, moisture, soil type, and seed depth (Davis et al. 2013; Forcella et al. 1997, 2000; Renner et al. 1999). However, most of the current models are based on no-till or single-date tillage experiments in maize/soybean systems in central USA, not representative of the frequent disturbance present at diversified farms in northeastern USA. Thus, our objective was to compare species emergence resulting from a full range of tillage dates to previous research and provide a review of ecologically based management tactics that could be improved with enhanced knowledge of emergence periodicity.

Materials and Methods

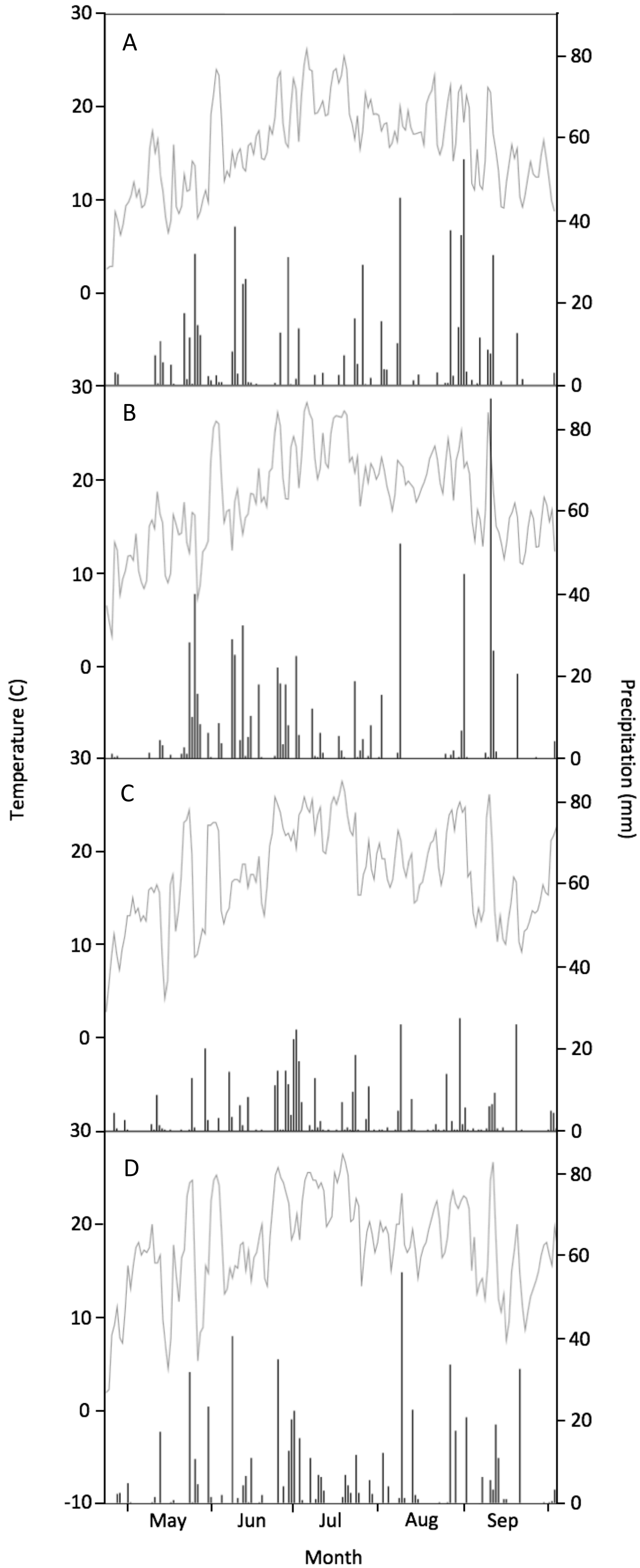
In 2013, field experiments were established at four locations: the University of Maine Rogers Farm (hereafter 'Rogers'), Old Town, ME 44.93°N, 68.69°W), the University of New Hampshire Woodman Horticultural Research Farm (hereafter 'Woodman'), Durham, NH (43.15°N, 70.94°W), Big Flats Plant Materials Center (hereafter 'Big Flats'), Big Flats, NY (42.16°N, 76.89°W), and Musgrave Research Farm (hereafter 'Musgrave'), Aurora, NY (42.73°N, 76.66°W). The soil type was Lamoine silt loam at Rogers, Charlton fine sandy loam at Woodman, Univilla silt loam at Big Flats, and Lima silt loam at Musgrave. Experimental treatments consisted of rototilling (to 15 cm depth) new plots every two weeks from April 29 to September 30, except at Rogers, where the end date was September 16. Plots were 1.5 by 3.0 m, set up in a randomized complete block design with four replicates (five at Woodman). Plots were located in field centers to avoid spread of species from the field edge. Prior to the first tillage date, the field at Musgrave was sprayed with glyphosate (Roundup, Monsanto, St. Louis, MO 63137) at 340 g ai ha^{-1} to suppress crop volunteers and increase the likelihood that emergence of perennial weeds was from seed. Within blocks, treatments were assigned to experimental plots at random to account for patchiness of distributions within fields.

A total of 196 plots were sampled over the four sites. Weed density by species was measured 6 wk after each tillage event to allow enough time for sufficient emergence while avoiding the weed-weed competition that may suppress some individuals. Sampling consisted of identifying and counting all seedlings in two randomly located quadrats (50 by 50 cm each) for each plot. The two quadrats were averaged and converted to stems m^{-2}.

For the five most abundant agronomic weeds at each site, many of which were cited by farmers as the most problematic weeds of maize and soybean systems in midwestern USA (Gibson et al. 2006) and vegetable systems in northeastern USA (Jabbour et al. 2014a), violin plots of emergence data were prepared using ggplot2 package in R (Wickham 2009). The smoothing ratio was set equal to one for all species except hairy galinsoga (*Galinsoga quadriradiata* Cav.) at Rogers Farm, large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and mouseear chickweed (*Cerastium vulgatum* L.) at Woodman, and smooth crabgrass [*Digitaria ischaemum* (Schreb.) Schreb. ex Muhl.] at Big Flats, which were set at 1.5, 1.5, 3.0, and 3.5, respectively, in order to reduce the prominence of peaks at sampling dates. The number of occurrences of the five most abundant species at each site ranged from 42 to 10,872. Violin plots were separated by site because conditions and resulting emergence were different at each location.

Weather data were obtained from nearby weather stations (NOAA 2013) (Figure 5.1.). Daily mean air temperature was calculated by taking the average of the daily maximum and minimum temperatures. Weather data was used to predict peak emergence based on previous modeling research (Archer et al. 2006; Werle et al. 2014b) that used growing degree-days in order to provide a basis for comparison between simulated emergence and our empirical results.

Figure 5.1. Air temperature (line) and precipitation (bars) for the study period at locations; Rogers Farm, Old Town, ME (A); Woodman Horticultural Research Farm, Durham, NH (B), Big Flats Plant Materials Center, Big Flats, NY (C), and Musgrave Research Farm, Aurora, NY (D).

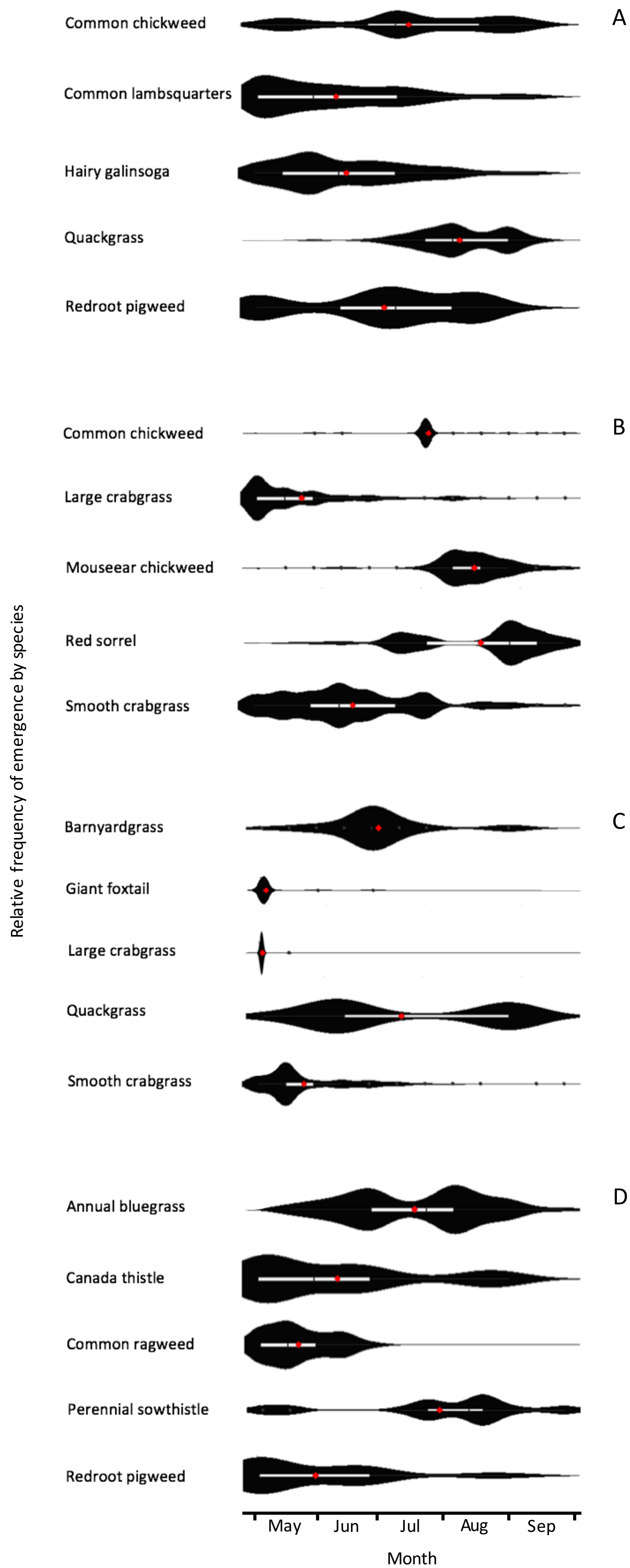


Results and Discussion

Emergence Periodicity

Overall, the peaks and spread of emergence varied greatly between species (Figure 5.2.), likely representing different patterns of minimum dormancy between species (Probert 1992). Emergence was earliest for most summer annual species, including barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], common lambsquarters (*Chenopodium album* L.), common ragweed (*Ambrosia artemisiifolia* L.), giant foxtail (*Setaria faberi* Herrm.), large crabgrass, redroot pigweed (*Amaranthus retroflexus* L.), and smooth crabgrass. Hairy galinsoga demonstrated a slightly delayed emergence compared to the other summer annuals. Later emergence was observed for winter annuals, including common chickweed [*Stellaria media* (L.) Vill] and annual bluegrass (*Poa annua* L.), as well as perennials, including Canada thistle [*Cirsium arvense* (L.) Scop.], mouseear chickweed, perennial sowthistle (*Sonchus arvensis* L.), red sorrel (*Rumex acetosella* L.), and quackgrass [*Elymus repens* (L.) Gould].

Figure 5.2. Violin plots of emergence of the five most abundant weeds resulting from a range of tillage dates at locations; Rogers Farm, Old Town, ME (A); Woodman Horticultural Research Farm, Durham, NH (B), Big Flats Plant Materials Center, Big Flats, NY (C), and Musgrave Research Farm, Aurora, NY (D). Plot were constructed with ggplot2 package in R (Wickham 2009). The smoothing ratio was set to one for all species except hairy galinsoga at Rogers, large crabgrass and mouseear chickweed at Woodman, and smooth crabgrass at Big Flats, which were set at 1.5, 1.5, 3.0, and 3.5, respectively, in order to reduce the prominence of peaks at multiple sampling dates. Box plots are presented within violin plots and means represented by red dots.



The tillage dates resulting in maximum observed emergence generally agreed with the peak emergence dates found by previous empirical studies based on emergence in no-till or single-date tillage experiments in different regions (Table 5.1.), indicating that emergence trends are somewhat robust to variation in tillage regime and geography. Notable deviations include later emergence of perennial sowthistle and quackgrass. These species initiate shoot elongation early (Donald 2000; Torssell et al. 2015), indicating the pre-season application of glyphosate likely killed ambient rhizomes, and that the emergence we observed was from seed. Additionally, annual bluegrass, a winter annual, showed sizable early and late emergence peaks at Musgrave in contrast to previous studies finding a mostly autumn emergence (Table 5.1.). Perhaps this difference highlights a trend of autumn emergence of problematic winter annuals in midwestern USA (Werle et al. 2014a) versus spring and autumn emergence in more northern climes (Cici et al. 2009).

Table 5.1. Comparison of tillage dates resulting in maximum weed emergence to previous work on peak emergence. Asterisks indicate locations of our field experiments. Results in italics were calculated using existing emergence models with weather data from our field sites.

Species	Location	Tillage date(s) resulting in maximum emergence	Previous studies of peak emergence
Annual bluegrass	Musgrave*	June 23 and Aug. 4	
	California, USA		November 5 (Shem-Tov and Fennimore 2003)
	Maryland, USA		Late September to mid-October (Kaminski and Dernoeden 2007)
	Illinois, USA		Spring and autumn (Branham 1991
Barnyardgrass	Big Flats*	June 23	*May 30 (Archer et al. 2006), June 2 (Werle et al. 2014b)*
	Ontario, Canada		June (Maun and Barrett 1986)
	Massachusetts, USA		June but through September (Vengris 1965)
	Czech Republic		May and June (Jursik et al. 2014)
Canada thistle	Musgrave*	April 28	*April 19 (Hodgson 1964), March 31 to April 19 (Hodgson 1955)*
	Montana, USA		Early May (Hodgson 1964)
	Idaho, USA		March and April (Hodgson 1955)
Common chickweed	Rogers	July 7	*July 24 (Hill et al. 2014), May 31 (Grundy et al. 2003)*

Table 5.1. Continued.

	Woodman	July 21	*July 9 (Hill et al. 2014), May 17 (Grundy et al. 2003)*
	Warwick, England		Continuously but mostly early spring or late autumn (Roberts and Dawkins 1967)
Common lamsquarters	Rogers*	April 28	*May 26 (Archer et al. 2006), May 24 (Leblanc et al. 2004), June 7 (Werle et al. 2014b)*
	Czech Republic		March and April (Jursik et al. 2014)
	Minnesota, USA		April 22 to May 4 (Harvey and Forcella 1993)
	Quebec, Canada		May 30 (Leblanc et al. 2004)
	Ontario, Canada		May 30 to June 19 (Roman et al. 2000)
	Wisconsin, USA		June 9 and 13 for till and no-till, respectively (Buhler et al. 1996)
	Mid-Atlantic states, USA		Sites ranged from May 11 to June 1 (Myers et al. 2004)
Common ragweed	Musgrave*	May 12	*May 11 (Archer et al. 2006), May 6 (Werle et al. 2014b)*
	Illinois, USA		April and May, none after June 1 (Stoller and Wax 1973)
	Ontario, Canada		90% emergence prior to June 15 (Bassett and Crompton 1975)
	New York, USA		Prior to June 9 (Dickerson 1968)
	Mid-Atlantic states, USA		Sites ranged from April 7 to May 1 (Myers et al. 2004)
Giant foxtail	Big Flats*	April 28	*May 16 (Archer et al. 2006), June 1 (Werle et al. 2014b)*

Table 5.1. Continued.

	Wisconsin, USA		June 7 and 8 for no till and till, respectively (Buhler et al. 1996)
	Mid-Atlantic states, USA		Sites ranged from May 2 to May 24 (Myers et al. 2004)
	Ohio, USA		May 16 to 18 depending on tillage (Cardina et al. 2007)
Hairy galinsoga	Rogers*	May 26	
	Multiple locations		May and June but continues throughout season (Warwick and Sweet 1983)
	Czech Republic		June and July. Later than other summer annuals (Jursik et al. 2014)
Large crabgrass	Woodman*	April 28	*June 25 (Cardina et al. 2011)*
	Big Flats*	April 28	*June 23 (Cardina et al. 2011)*
	Arkansas, USA		Two weeks after spring tillage dates (King and Oliver 1994)
	Mid-Atlantic states, USA		Sites ranged from May 18 to June 8 (Myers et al. 2004)
	Ohio, USA		June 7 (Cardina et al. 2011)
Mouseear chickweed	Woodman*	Aug. 4	
Perennial sowthistle	Musgrave*	July 21 and Aug. 18	
	Uppsala, Sweden		Late April shoot growth of established stands (Hakansson 1969)
	Plains USA and Canada		Seed germination in late-May (Lemna and Messersmith 1990)

Table 5.1. Continued.

Quackgrass	Big Flats*	June 9 and Sept. 1	
	Rogers*	Aug. 4 and Sept. 1	
	Multiple locations		Seed and rhizome sprouts emerge in early spring (Werner and Rioux 1977)
	Rothamsted, England		Seeds germinated readily in spring as well as autumn sowings (Williams 1971)
Red sorrel	Woodman*	Sept. 1	*50% ramet emergence June 27 (White et al. 2015)*
	Victoria, Australia		Seed emerged mostly in autumn (Amor 1985)
Redroot pigweed	Rogers*	July 7	*May 23 (Archer et al. 2006), July 19 (Werle et al. 2014b)*
	Musgrave*	April 28	*May 23 (Archer et al. 2006) July 2 (Werle et al. 2014b)*
	Czech Republic		Late April and May (Jursik et al. 2014)
	Wisconsin, USA		June 7 and June 9 for no-till and till, respectively (Buhler et al. 1996)
Smooth crabgrass	Woodman*	June 9	*June 25 (Fidanza et al. 1996), May 23 (Cardina et al. 2011)*
	Big Flats*	May 12	*June 23 (Fidanza et al. 1996), May 23 (Cardina et al. 2011)*
	Maryland, USA		Early June (Fidanza et al. 1996)
	Ohio, USA		May 10 (Cardina et al. 2011)

Management Recommendations

We grouped management recommendations based on early-, mid-, and late-season peak emergence (Table 5.2.). Foremost, stale seedbed periods corresponding with the emergence peak of the target species may be used to maximize germination and debits to the weed seedbank (Gallandt 2006). Similarly, the timing of crop planting could be adjusted to avoid crop losses due to the timing of weed competition (Knezevic et al. 2002). Delaying planting may reduce the yield potential in some crops, which must be weighed against weed management benefits. Since crops differ in planting dates and associated management (Liebman and Gallandt 1997), planting date may factor into crop or variety choice. Early autumn bare fallow periods could be used to target perennials by severing roots and shoots to exhaust carbohydrate reserves (Andersson et al. 2013).

Table 5.2. Weed management options based on peak emergence of targeted weeds in temperate climates.

Management tactic	Early (March-May)	Mid (June-July)	Late (August-October)
Stale seedbed timing	Pre-plant stale seedbed (Oliver et al. 1993)	If possible, shift planting to accommodate stale seedbed.	Post-harvest stale seedbed period.
Timing of crop planting	Delay planting to avoid peak emergence (Gill and Holmes 1997).	Consider growing cool season crops that are harvested before or planted after peak emergence (DeVore et al. 2011).	Plant earlier to avoid peak emergence.
Cover crop considerations	Establish cover crops around peak emergence dates and incorporate prior to weeds setting seed (Sarrantonio and Gallandt 2003).	If using a full-year of cover crops, allow for a mid-season stale seedbed (Nordell and Nordell 2009).	Delay cover crop planting to allow for an autumn stale seedbed. Compensate with an increased cover crop seeding rate.
Weed suppression	Use cover crop residue to reduce weed emergence by allelopathy (Weston and Duke 2003) or by acting as a mulch (Carrera et al. 2004).	Increase planting density (Mohler 1996) and use living mulches (Hartwig and Ammon 2002) to suppress mid-season weeds.	Late germinating weeds are often suppressed by crop canopy but may flourish after harvest in no-till systems. Use an overseeded cover crop to provide continuous suppression (Smith 2005).
Mechanical weed control	Use shallow cultivations to control weeds and promote subsequent flushes in stale seedbed but use flaming or herbicides as a final control (Caldwell and Mohler 2001).	Cultivation around peak emergence to control weeds in the sensitive "white thread" stage (Liebman et al. 2001).	Till post-harvest to prevent weeds from setting seed. If seeds are already present, delay tillage to allow for seed predation (Birthisel et al. 2015) and advanced recruitment the following spring (Gallandt unpublished).
Pre-emergent herbicides	May not be needed if most emergence occurs prior to seedbed preparation.	Apply slightly before peak emergence (Forcella 1999).	Apply to reduce emergence in winter cover crops (Walters et al. 2007).

Table 5.2. Continued.

Post-emergent herbicides	Apply burndown herbicides prior to planting.	Apply during or just after peak emergence while weeds are small (Forcella 1999).	Apply burndown herbicides to control in-season escapes (Crow et al. 2015) and lessen overwintering weed density the following spring (Hasty et al. 2004)

Taking land out of production for a full year of cover cropping allows for the establishment of a stale seedbed period at any desired time (Nordell and Nordell 2009). A full year of rapid succession cover crops that are incorporated before weeds have time to set seed is an effective way to reduce the weed seedbank (Mirsky et al. 2010; Sarrantonio and Gallandt 2003; Sideman 2013), while the cover crop biomass is thought to compensate for the negative effects of tillage (Gallandt 2006). Perhaps this method could be adjusted so that the cover crop seedbed preparation dates align with peak emergence of problem weed species so germination is encouraged but incorporation of the cover crop occurs prior to setting seed. For farmers unable to cover crop for a full season, a short-term cover crop established at the target weed's peak emergence may be used for a similar effect.

Weed suppression tactics may also be informed by the emergence periodicity of problem weeds. Natural mulches may provide early suppression, but control may decline as the mulch decays in the late-season (Law et al. 2006). Planting density may be used to facilitate mid-season canopy closure (Mohler 1996) and overseeded cover crops allow for post-harvest suppression (Smith 2005).

Frequent in-season cultivations can be used to control weeds in the sensitive "white thread" stage, especially for intra-row control, but perhaps cultivation could be more efficient if focused around peak emergence periods of problem weeds. Due to crop height or spread, mechanical cultivation may not be possible to control weeds that emerge in the late season. However, immediate post-harvest tillage may attempt to control these weeds prior to setting seed.

Both pre- and post-emergence herbicide applications should be guided by weed emergence (Forcella 1999; Zimdahl 2007). Premature applications of pre-emergence herbicides allow the chemical to break down prior to peak emergence whereas late applications are less effective against already emerged weeds. For this reason, planting dates may be adjusted to allow for optimal pre-emergence herbicide control (Culpepper et al. 2004; Webster et al. 2009). Likewise, post-emergence herbicides should be applied soon after peak weed emergence periods to avoid ineffective or over-application (Fidanza et al. 1996; Masin et al. 2005). Overall, well-timed, highly effective herbicide applications could reduce the amount or frequency of spraying, which could minimize development of herbicide resistance (Norsworthy et al. 2012) and reduce harmful environmental effects (Liebman et al. 2001). Furthermore, improved understanding of emergence periodicity could benefit integrated weed management efforts by improving physical and cultural controls, thereby lessening the selection pressure from herbicides (Norsworthy et al. 2012; Soteres et al. 2013).

Unfortunately, many species exhibited a protracted emergence pattern (Figure 5.2.) rather than an easily manageable cohort (Forcella 1999). Protracted emergence can allow late emerging weeds to escape control (Neve et al. 2003; Reddy and Norsworthy 2010) or be subjected to sublethal herbicide doses (Zhang et al. 2000), which may encourage resistance (Manalil et al. 2011). Protracted emergence is problematic for non-chemical management as well. The protracted emergence of hairy galinsoga allows it to evade spring stale-seedbed periods as well as early cultivations and may contribute to its status as the most problematic weed among northern New England organic farmers (Jabbour et al. 2014a). Thus, although late emerging weeds may not affect yield (Knezevic et al. 2002), they should still be controlled from a resistance management (Jha et al. 2008) and seedbank management perspective (Norris 1999). An “all of the above” strategy may be necessary to control species with protracted emergence but the practices described in the Mid- and Late-Season columns of Table 5.2. are likely most applicable.

Overall, for most species investigated, tillage dates resulting in maximum emergence were within or near the range of peak emergence dates reported by previous studies. These peak emergence periods may be used to improve implementation of ecologically based weed management tactics. However, many species exhibited protracted emergence, which may require extended control tactics as part of an herbicide resistance management and seedbank management approach.

REFERENCES

Abu-Awwad AM (1999) Irrigation water management for efficient water use in mulched onion. J Agron Crop Sci 183:1–7

Akaike H (1974) A new look at the statistical model identification. Trans Auto Control 19:716–723

Alford AR, Garcıa SC, Farina S, Fulkerson WJ (2009) An economic evaluation of the future dairy complementary forage rotation system – using cost budgeting. Armidale, Australia: Economic Research Report No. 44. Industry and Investment NSW

Amor R (1985) Seasonal emergence of weeds typically occurring in the Victorian wheat belt (Australia). Plant Prot Quart 1:18-20

Anderson J M, Ingram JSI (1989) Tropical soil biology and fertility: A handbook of methods. Wallingford: CAB International. Pp 101–102

Anderson RL (2005) A multi-tactic approach to manage weed population dynamics in crop rotations. Agron J 97:1579–1583

Andersson L, Boström U, Forkman J, Hakman I, Liew J, Magnuski E (2013) Sprouting capacity from intact root systems of *Cirsium arvense* and *Sonchus arvensis* decrease in autumn. Weed Res 53:183–191

Anisuzzaman M, Ashrafuzzaman M, Ismail MR, Uddin MK, Rahim MA (2009) Planting time and mulching effect on onion development and seed production. Afr J Biotechnol 8:412–416

Archer DW, Forcella F, Korth A, Kuhn A, Eklund J, Spokas, K (2006) WeedCast. http://www.ars.usda.gov/services/software/download.htm?softwareid 5112. Accessed March 20, 2016

Ascard J, Fogelberg F (2008) Mechanical in-row weed control in transplanted and direct-sown bulb onions. Biol Agr Hort 25:235–251

Baerveldt S, Ascard J (1999) Effect of soil cover on weeds. Biol Agr Hort 17:101–111

Bagavathiannan MV, Norsworthy JK (2012) Late-season seed production in arable weed communities: Management implications. Weed Sci 60:325–334

Baker BP, Mohler CL (2014) Weed management by upstate New York organic farmers: Strategies, techniques and research priorities. Renew Agr Food Syst 30:1–10

Bassett IJ, Crompton CW (1975) The biology of Canadian weeds. 11. *Ambrosia artemisiifolia* L. and *A. psilostachya* DC. Can J Plant Sci 55:463–476

Bastiaans L, Paolini R, Baumann DT (2008) Focus on ecological weed management: What is hindering adoption? Weed Res 48:481–491

Bengough AG, Young IM (1993) Root elongation of seedling peas through layered soil of different penetration resistances. Plant Soil 149:129–139

Bernard HR (2011) Research methods in anthropology - Qualitative and quantitative approaches. 5th ed. Oxford, UK: AltaMira Press

Birthisel SK, Gallandt ER, Jabbour R (2014) Habitat effects on second-order predation of the seed predator *Harpalus rufipes* and implications for weed seedbank management. Biol Control 70:65–72

Birthisel SK, Gallandt ER, Jabbour R, Drummond FA (2015) Habitat and time are more important predictors of weed seed predation than space in a Maine USA mixed vegetable agroecosystem. Weed Sci 63:916–927

Bond W, Burston S (1996) Timing the removal of weeds from drilled salad onions to prevent crop losses. Crop Prot 15:205–211

Bond W, Burston S, Moore HC (1998) Changes in the weed seedbank following different weed control treatments in transplanted bulb onions grown organically and conventionally. Asp App Biol 51:273–296

Bowman G (2002) Steel in the field: A farmer’s guide to weed management tools. Beltsville, MD: Sustainable Agriculture Network

Box GEP, Cox DR (1964) An analysis of transformations. J R Stat Soc Series B 26:211–252

Branham B (1991) Dealing with *Poa annua*. Golf Course Manag 59:46–50

Brault D, Stewart KA, Jenni S (2002) Growth, development, and yield of head lettuce cultivated on paper and polyethylene mulch. HortScience 37:92–94

Brewster JL (2008) Onions and Other Vegetable Alliums. 2nd edn. Wallingford, UK. CAB international. Pg 173–176

Buhler DT, Mester C, Kohler K (1996) The effect of maize residues and tillage on emergence of *Setaria faberi, Abutilon theophrasti, Amaranthus retroflexus* and *Chenopodium album*. Weed Res 36:153–165

Caldwell B, Mohler CL (2001) Stale seedbed practices for vegetable production. Hortic Sci 36:703-705

Caldwell B, Mohler CL, Ketterings QM, DiTommaso A (2014) Yields and profitability during and after transition in organic grain cropping systems. Agron J 106:871–880

Cardina J, Herms CP, Herms DA (2011) Phenological indicators for emergence of large and smooth crabgrass (*Digitaria sanguinalis* and *D. ischmaemum*). Weed Technol 25:141–150

Cardina J, Herms CP, Herms DA, Forcella F (2007) Evaluating phenological indicators for predicting giant foxtail (*Setaria faberi*) emergence. Weed Sci 55:455-464

Carrera LM, Abdul-Baki AA, Teasdale JR (2004) Cover crop management and weed suppression in no-tillage sweet corn production. Hortscience 39:1262–1266

Chan S, Caldwell BA, Rickard BJ, Mohler CL (2011) Economic performance of organic cropping systems for vegetables in the Northeast. J Agribusiness 29:59–81

Cici SZH, Van Acker RC (2009) A review of the recruitment biology of winter annual weeds in Canada. Can J Plant Sci 89:575–589

Cirujeda A, Aibar J, Anzalone A, Martín-Closas L, Meco R, Moreno MM, Pardo A, Pelacho AM, Rojo F, Royo-Esnal A, Suso AM, Zaragoza C (2012) Biodegradable mulch instead of polyethylene for weed control of processing tomato production. Agron Sustain Dev 32:889–897

Cirujeda A, Taberner A (2004) Defining optimal conditions for weed harrowing in winter cereals on *Papaver rhoeas* L. and other dicotyledoneous weeds. Lilliehammer, Norway: 6th EWRS Workshop on Physical and Cultural Weed Control

Colby SR (1967) Calculating synergistic and antagonistic responses of herbicide combinations. Weeds 15:20-22

Cox WJ, Singer JS, Shields EJ, Waldron JK, Bergstrom GC (1999) Agronomics and economics of different weed management systems in corn and soybean. Agron J 91:585– 591

Crow WD, Steckel LE, Hayes RM, Mueller TC (2015) Evaluation of POST-harvest herbicide applications for seed prevention of glyphosate-resistant Palmer amaranth (*Amaranthus palmeri*). Weed Technol 29:405–411

Culpepper AS, Flanders JT, York AC, Webster TM (2004) Tropical spiderwort (*Commelina benghalensis*) control in glyphosate-resistant cotton. Weed Technol 18:432-436

Davis AS, Clay S, Cardina J, Dille A, Forcella F, Lindquist J, Sprague C (2013) Seed burial physical environment explains departures from regional hydrothermal model of giant ragweed (*Ambrosia trifida*) seedling emergence in U.S. Midwest. Weed Sci 61:415–421

Davis AS, Hill JD, Chase CA, Johanns AM, Liebman M (2012) Increasing cropping system diversity balances productivity, profitability and environmental health. PloS One doi:10.1371/journal.pone.0047149

DeDecker JJ, Masiunas JB, Davis AS, Flint CG (2014) Weed management practice selection among Midwest U.S. organic growers. Weed Sci 62:520–531

DeVore JD, Norsworthy JK, Johnson DB, Starkey CE, Wilson MJ, Griffith GM (2011) Palmer amaranth emergence as influenced by soybean production system and deep tillage. Proc South Weed Sci Soc 64:239

Dieleman JA, Mortensen DA, Martin AR (1999) Influence of velvetleaf (*Abutilon theophrasti*) and common sunflower (*Helianthus annuus*) density variation on weed management outcomes. Weed Sci 47:81–89

Donald WW (2000) A degree-day model of *Cirsium arvense* shoot emergence from adventitious root buds in spring. Weed Sci 48:333–341

Edwards CA, Lofty JR (1977) Biology of earthworms. 2nd ed. Rothamsted Experiment Station, Chapman & Hall, London. Pp 118–119

Evans GJ, Bellinder RR, Hahn RR (2012) An evaluation of two novel cultivation tools. Weed Technol 26:316–325

Farias-Larios J, Orozco-Santos M (1997) Effect of polyethylene mulch colour on aphid populations, soil temperature, fruit quality, and yield of watermelon under tropical conditions. New Zeal J Crop Hort 25:369–374

Fennimore SA, Slaughter DC, Siemens MC, Leon RG, Saber MN (2016) Technology for automation of weed control in specialty crops. Weed Technol 30:823–837

Ferreira IQ, Rodrigues MÂ, Claro AM, Arrobas M (2015) Management of nitrogen-rich legume cover crops as mulch in traditional olive orchards. Commun Soil Sci Plant Analysis. 46:1881–1894

Fidanza MA, Dernoeden PH, Zhang M (1996) Degree-days for predicting smooth crabgrass emergence in cool-season turfgrass. Crop Sci 36:990–996

Forcella F (1999) Estimating the timing of weed emergence. Site Specific Management Guidelines. International Plant Nutrition Institute. 4 p

Forcella F (2003) Debiting the seedbank: priorities and predictions. Asp Appl Biol 69:151– 162

Forcella F, Eradat-Oskoui K, Wagner SW (1993) Application of weed seedbank ecology to low-input crop management. Ecol Appl 3:74–83

Forcella F, Wilson RG, Dekker J, Kremer RJ, Cardina J, Anderson RL Alm D, Renner KA, Harvey H, Clay S, Buhler DD (1997) Weed seed bank emergence across the corn belt. Weed Sci 45:67–76

Gallandt ER (2014) Weed management in organic farming. In: *Recent Advances in Weed Management,* (eds BS Chauhan & G Mahajan) 63–85. New York: Springer

Gallandt ER (2006) How can we target the weed seedbank? Weed Sci 54:588–596

Gallandt ER, Brainard DC, Brown B. (2017) Developments in physical weed control. In: *Integrated Weed Management for Sustainable Agriculture,* (ed RL Zimdahl) pages. Sawston, UK: Burleigh Dodds Science Publishing

Gallandt ER, Molloy T, Lynch RP, Drummond FA (2005) Effect of cover-cropping system on invertebrate seed predation. Weed Sci 53:69–76

Gallandt ER, Liebman M, Corson S, Porter GA, Ullrich SD (1998) Effects of pest and soil management systems on weed dynamics in potato. Weed Sci 46:238-248

Gibson AKD, Johnson WG, Hillger DE (2006) Farmer perceptions of weed problems in corn and soybean rotation systems. Weed Technol 20:751–755

Gifford EM, Stewart KD (1965) Ultrastructure of vegetative and reproductive apices of *Chenopodium album*. Science 149:75–77

Gill GS, Holmes JE (1997) Efficacy of cultural control methods for combating herbicide-resistant *Lolium rigidum*. Pestic Sci 51:352-358

Grubinger V (2005) Managing nitrogen on organic farms. The University of Vermont Extension. https://www.uvm.edu/vtvegandberry/factsheets/managingNorganic.html. Accessed October 3 2016

Grundy AC, Peters NCB, Rasmussen IA, Hartmann KM, Sattin M, Andersson L, Mead A, Murdoch AJ, Forcella, F (2003) Emergence of *Chenopodium album* and *Stellaria media* of different origins under different climatic conditions. Weed Res 43:163–176

Hakansson S (1969) Experiments with Sonchus arvensis L. I. Development and growth and response to burial and defoliation in different developmental stages. Lantbrukshogsk. Ann 35:989–1030

Halloran JM, Griffin TS, Honeycutt CW (2005) An economic analysis of potential rotation crops for Maine potato cropping systems. Am J Potato Res 82:155–162

Hardaker JB, Huirne RBM, Anderson JR, Lien G (2004) Coping with risk in agriculture. Oxfordshire: CAB International Publishing

Hartwig NL, Ammon HU (2002) Cover crops and living mulches. Weed Sci 50:688–699

Hartzler RG, Roth GW (1993) Effect of prior year's weed control on herbicide effectiveness in corn (*Zea mays*). Weed Technol 7:611–1614

Harvey SJ, Forcella F (1993) Vernal seedling emergence model for common lambsquarters (*Chenopodium album*). Weed Sci 41:309–316

Hasty RF, Sprague CL, Hager AG (2004) Weed control with fall and early preplant herbicide applications in no-till soybean. Weed Technol 18:887–892

Hewson RT, Roberts HA (1971) The effects of weed removal at different times on the yield of bulb onions. J Hort Sci 46:471–483

Hill DE, Hankin L, Stephens GR (1982) Mulches: Their effect on fruit set, timing and yields of vegetables. The Connecticut Agricultural Experiment Station Bulletin. p 8

Hill EC, Renner KA, Sprague CL (2014) Henbit (*Lamium amplexicaule*), common chickweed (*Stellaria media*), shepherd's-purse (*Capsella bursa-pastoris*), and field pennycress (*Thlaspi arvense*): Fecundity, seed dispersal, dormancy, and emergence. Weed Sci 62:97–106

Hodgson JM (1955) Whitetop and its control. Idaho Agricultural Experiment Station Bulletin 243. 18p

Hodgson JM (1964) Variations in ecotypes of Canada thistle. Weeds 13:167-171

Holm RE (1972) Volatile metabolites controlling weed germination in soil. Plant Physiol 50:293–297

Hopp H, Hopkins HT (1946) Earthworms as a factor in the formation of water-stable soil aggregates. J Soil Water Cons 1:11-13

Islam KR, Weil RR (2000) Soil quality indicator properties in mid-Atlantic soils as influenced by conservation management. J Soil Water Cons 55:69–78

Jabbour R, Zwickle S, Gallandt ER, McPhee KE, Wilson RS, Doohan D (2014) Mental models of organic weed management: Comparison of New England US farmer and expert models. Renewable Agriculture and Food Systems. Renew Agr Food Syst 29:319–333

Jabbour R, Gallandt ER, Zwickle S, Wilson RS, Doohan D (2014) Organic farmer knowledge and perceptions are associated with on-farm weed seedbank densities in northern New England. Weed Sci 62:338–349

Jha P, Norsworthy JK, Bridges W Jr, Riley MB (2008) Influence of glyphosate timing and row width on Palmer amaranth (*Amaranthus palmeri*) and pusley (*Richardia* spp.) demographics in glyphosate-resistant soybean. Weed Sci 56:408–415

Jursik M, Holec J, Soukup J (2014) Polní vzcházivost plevelů v průběhu vegetace cukrovky (Field emergence of weeds during the growing season of sugar beet) Listy Cukrovarnické a Reparské 130:166–172

Kaminski JE, Dernoeden PH (2007) Seasonal *Poa annua* L. seedling emergence patterns in Maryland. Crop Sci 47:775–781

Kaya C, Higgs D, Kirnak H (2005) Influence of polyethylene mulch, irrigation regime, and potassium rates on field cucumber yield and related traits. J Plant Nutr 28:1739–1753

King CA, Oliver LR (1994) A model for predicting large crabgrass (*Digitaria sanguinalis*) emergence as influenced by temperature and water potential. Weed Sci 42:561–567

Knezevic SZ, Evans SP, Blankenship EE, Acker RC Van, Lindquist JL (2002) Critical period for weed control: The concept and data analysis. Weed Sci 50:773–786

Kolb LN, Gallandt ER, Molloy T (2010) Improving weed management in organic spring barley: Physical weed control vs. interspecific competition. Weed Res 50:597–605

Kolb LN, Gallandt ER, Mallory EB (2012) Impact of spring wheat planting density, row spacing, and mechanical weed control on yield, grain protein, and economic return in Maine. Weed Sci 60:244–253

Kopittke PM, Menzies NW (2007) A review of the use of the basic cation saturation ratio and the "ideal" soil. Soil Sci 71: 259-265.

Kouwenhoven JK, Terpstra R (1979) Sorting action of tines and tine-like tools in the field. J Agr Eng Res 24:95–113

Kruskal WH, Wallis WA (1952) Use of ranks in one-criterion variance analysis. J Am Stat Assoc 47:583–621

Kurstjens DAG, Kropff MJ (2004) Method for predicting selective uprooting by mechanical weeders from plant anchorage forces. Weed Sci 52:123–132

Kurstjens DAG, Perdok UD (2000) The selective soil covering mechanism of weed harrows on sandy soil. Soil Tillage Res 55:193-206

Kurstjens DAG, Perdok UD, Goense D (2000) Selective uprooting by weed harrowing on sandy soils. Weed Res 40:431–447

Lament WJ (1993) Plastic mulches for the production of vegetable crops. HortTechnology 3:35–39

Larentzaki E, Plate J, Nault BA, Shelton AM (2008) Impact of straw mulch on populations of onion thrips (Thysanoptera: Thripidae) in onion. J Econ Entomol 101:1317–1324

Larsen T, Saxena A, Cramer CS. (2009) Relatedness of bulb firmness to other attributes of New Mexico onion entries. Int J Veg Sci 15:206–217

Law DM, Rowell AB, Snyder JC, Williams MA (2006) Weed control efficacy of organic mulches in two organically managed bell pepper production systems. HortTechnology 16:225–232

Lazarus WF (2015) Machinery cost estimates. St. Paul, MN: University of Minnesota Extension

Leblanc ML, Cloutier DC, Stewart KA, Hamel C (2004) Calibration and validation of a common lambsquarters (*Chenopodium album*) seedling emergence model. Weed Sci 52:61–66

Lemna WK, Messersmith CG (1990) The biology of Canadian weeds. 94. Sonchus arvensis L. Can J Plant Sci 70:509-532

Liebman M (2001) Weed management: A need for ecological approaches. Pages 1-30 in Leibman M, Mohler CL, Staver CP, eds. Ecological Management of Agricultural Weeds. New York: Cambridge University Press

Liebman M, Gallandt ER (1997) Many little hammers: Ecological management of crop-weed interactions. Pages 291–343 in Jackson LE eds. Ecology in Agriculture. New York: Academic Press

Lonsbary SK, O'Sullivan J, Swanton CJ (2003) Stale-seedbed as a weed management alternative for machine-harvested cucumbers (*Cucumis sativus*). Weed Technol 17:724–730

Lu Y-C, Watkins B, Teasdale J (1999) Economic analysis of sustainable agricultural cropping systems for Mid-Atlantic states. J Sustain Agric 15:77–93

Lundkvist A (2009) Effects of pre- and post-emergence weed harrowing on annual weeds in peas and spring cereals. Weed Res 49:409–416

Manalil S, Busi R, Benton M, Powles S (2011) Rapid evolution of herbicide resistance by low herbicide dosages. Weed Sci 59:210–217

Marshall EJ, Brown VK, Boatman ND, Lutman PJW, Squire GR, Ward LK (2003) The role of weeds in supporting biological diversity within crop fields. Weed Res 43:77–89

Masin R, Zuin MC, Archer DW, Zanin G (2005) WeedTurf: A predictive model to aid control of annual summer weeds in turf. Weed Sci 53:193–201

Maun MA, Barrett SCH (1986) The biology of Canadian weeds. 77. Echinochloa crus-galli (L.) Beauv. Can J Plant Sci 66:739–759

McCallum J, Clarke A, Pither-Joyce M, Shaw M, Butler R, Brash D, Scheffer J, Sims I, Vanheusden S, Shigyo M, Havey MJ (2006) Genetic mapping of a major gene affecting onion bulb fructan content. Theor Appl Genet 112:958–967

Melander B, Lattanzi B, Pannacci E (2015) Intelligent versus non-intelligent mechanical intra-row weed control in transplanted onion and cabbage. Crop Prot 72:1–8

Menges RM, Tamez S (1981) Common sunflower (*Helianthus annuus* L) interference in onions. Weed Sci 29:641–647

Mirsky SB, Gallandt ER, Mortensen DA, Curran WS, Shumway DL (2010) Reducing the germinable weed seedbank with soil disturbance and cover crops. Weed Res 50:341–352

Miyanishi K, Cavers PB (1980) The biology of Canadian weeds. 40. *Portulaca oleracea* L. Canadian Journal of Plant Science. 60:953–963

Mohler CL (2001) Mechanical management of weeds. In: *Ecological Management of Agricultural Weeds*, (eds M Liebman, CL Mohler, CP Staver), 139-209. Cambridge, UK: Cambridge University Press

Mohler CL, Iqbal J, Shen J, DiTommaso A (2016) Effects of water on recovery of weed seedlings following burial. Weed Sci 64:285–293

Mohler CL, Marschner CA, Caldwell BA, DiTommaso A (2016) Weed mortality caused by row-crop cultivation in organic corn–soybean–spelt cropping systems. Weed Technol 30:648–654

Mohler CL (1996) Ecological bases for the cultural control of annual weeds. J Prod Agr 9:468–474

Mohler CL (1993) A model of the effects of tillage on emergence of weed seedlings. Ecolog Appl 3:53–73

Mortensen DA, Bastiaans L, Sattin M (2000) The role of ecology in the development of weed management systems: An outlook. Weed Res 40:49–62

Mortensen DA, Johnson GA, Young LJ (1993) Weed distribution in agricultural fields. Pages 113-123 in Robert PC, Rust RH, Larson WE, eds. Soil Specific Crop Management. Madison, WI: Agronomy Society of America Press

Myers MW, Curran WS, Vangessel MJ, Calvin DD, Mortensen DA, Majek BA, Karsten HD, Roth GW (2004) Predicting weed emergence for eight annual species in the northeastern United States. Weed Sci 52:913–919

National Agricultural Statistics Service (2014) 2014 Organic Survey. https://www.agcensus.usda.gov/Publications/2012/Online_Resources/Organics/. Accessed 15 June 2016

National Oceanic and Atmospheric Association (2013) National Climatic Data Center. http://www.ncdc.noaa.gov/cdo-web/datatools/findstation. Accessed 2015 Dec 8

Neve P, Diggle AJ, Smith FP, Powles SB (2003) Simulating evolution of glyphosate resistance in *Lolium rigidum* I: Population biology of a rare resistance trait. Weed Res 43:404–417

Nieto HJ, Brondo MA, Gonzales J T (1968) Critical periods of the crop growth cycle for competition from weeds. PANS (C) 14:159–166

Nordell A, Nordell E (2009) Weed the soil, not the crop. Acres USA. 40:21–28

Norris R (1999) Ecological implications of using thresholds for weed management. J Crop Prod 2:31–58

Norsworthy JK, Ward SM, Shaw DR, Llewellyn RS, Robert L, Webster TM, Bradley KW, Frsivold G, Powles SB, Burgos NR, Witt WW, Barrett M (2012) Reducing the risks of herbicide resistance: Best management practices and recommendations. Weed Sci 60:31–62

Olsen J, Kristensen L, Weiner J (2005) Effects of density and spatial pattern of winter wheat on suppression of different weed species. Weed Science 53:690–694

Ott SL, Hargrove WL (1989) Profits and risks of using crimson clover and hairy vetch cover crops in no-till corn production. Am J Altern Agric 4:65–70

Özkan Ş, Farquharson RJ, Hill J, Malcolm B (2015) A stochastic analysis of the impact of input parameters on profit of Australian pasture-based dairy farms under variable carbon price scenarios. Environ Sci Policy 48:163–171

Pannell DJ, Malcolm B, Kingwell RS (2000) Are we risking too much? Perspectives on risk in farm modelling. Agric Econ 23:69–78

Petit S, Boursault A, Guilloux ML, Munier-Jolain N, Reboud X (2010) Weeds in agricultural landscapes. A review. Agron Sustain Dev 31:309–317

Pielou EC (1975) Ecological Diversity. New York: John Wiley and Sons

Probert RJ (1992) The role of temperature in germination ecophysiology. Pages 285–325 in Fenner M ed. The Ecology of Regeneration in Plant Communities. Wallingford, UK: CAB International

Proctor CA, Gaussoin RE, Reicher ZJ (2012) Vegetative reproduction potential of common purslane (*Portulaca oleracea*). Weed Technol 26:694–697

Pullen DWM, Cowell PA (1997) An evaluation of the performance of mechanical weeding mechanisms for use in high speed inter-row weeding of arable crops. J Agr Eng Res 67:27–34

Rasmussen J (1990) Selectivity-an important parameter on establishing the optimum harrowing technique for weed control in growing cereals. In: *Proceedings of EWRS symposium*, (4–6 June, Helsinki, Finland) 197-204. European Weed Research Society

Rasmussen J (1992) Testing harrows for mechanical control of annual weeds in agricultural crops. Weed Res 32:267–274

Rasmussen J, Ascard J (1995) Weed control in organic farming systems. In: *Ecology and Integrated Farming Systems.* (eds DM Glen, MP Greaves, and HM Anderson), 49-67. Chichester, UK: Wiley

Rasmussen J, Mathiasen H, Bibby BM (2010) Timing of post-emergence weed harrowing. Weed Res 50:436–446

Rasmussen J, Nørremark M, Bibby BM (2007) Assessment of leaf cover and crop soil cover in weed harrowing research using digital images. Weed Res 47:299–310

Rasmussen K, Rasmussen J (2000) Barley seed vigour and mechanical weed control. Weed Res 40:219–230

Rathers HC and Harrison CM (1951) Field Crops. New York: McGraw-Hill Book Company

Reddy KN, Norsworthy JK (2010). Glyphosate-resistant crop production systems: Impact on weed species shifts. Pages 165-184 in Nandula VK ed. Glyphosate Resistance in Crops and Weeds: History, Development, and Management. Singapore: Wiley

Renner K, Swinton S, Kells J (1999) Adaptation and evaluation of the WEEDSIM weed management model for Michigan. Weed Sci 47:338–348

Riemens M, Van Der Weide R, Bleeker P, Lotz L (2007) Effect of stale seedbed preparations and subsequent weed control in lettuce (cv. Iceboll) on weed densities. Weed Res 47:149–156

Riemens MM, Groaneveld RMW, Kropff M, Lotz LAP, Renes R, Sukkel W, Van Der Weide RY (2010) Linking farmer weed management behavior with weed pressure: More than just technology. Weed Sci 58:490–496

Riemens MM, Groeneveld RMW, Lotz LAP, Kropff MJ (2007) Effects of three management strategies on the seedbank, emergence and the need for hand weeding in an organic arable cropping system. Weed Res 47:442–451

Roberts HA, Dawkins PA (1967) Effect of cultivation on the numbers of viable weed seeds in the soil. Weed Res 7:290–301

Roberts HA, Feast PM (1972) Fate of seeds of some annual weeds in different depths of cultivated and undisturbed soil. Weed Res 12:316–324

Rogers EM (1988) Social change in rural societies: An introduction to rural sociology, 3rd ed. Englewood Cliffs, NJ: Prentice Hall

Roman ES, Murphy SD, Swanton CJ (2000) Simulation of *Chenopodium album* seedling emergence. Weed Sci 48:217–224

Ryan MR, Smith RG, Mirsky SB, Mortensen DA, Seidel R (2010) Management filters and species traits: Weed community assembly in long-term organic and conventional systems. Weed Sci 58:265–277

Rydberg T (1994) Weed harrowing - the influence of driving speed and driving direction on degree of soil covering and the growth of weed and crop plants. Biol Agr Hort 10:197–205

Saaty TL (1982) Decision making for leaders: The analytical hierarchy process for decisions in a complex world. Belmont, CA: Lifetime Learning Publications

Sanders DC, Cure JD, Schultheis JR (1999) Yield response of watermelon to planting density, planting pattern, and polyethylene mulch. HortScience 34:1221–1223

Sarrantonio M, Gallandt E (2003) The role of cover crops in North American cropping systems. J Crop Prod 8:53–74

Schonbeck MW (1998). Weed suppression and labor costs associated with organic, polyethylene, and paper mulches in small-scale vegetable production. J Sustain Agr 13:13–33

Schonbeck MW (2012) Organic Mulching Materials for Weed Management. http://www.extension.org/pages/65025/organic-mulching-materials-for-weed-management#.UscHxWRDvvi. Accessed March 1, 2014

Schonbeck MW, Evanylo GK (1998) Effects of mulches on soil properties and tomato production I. Soil temperature, soil moisture and marketable yield. J Sustain Agr 13:55–81

Schonbeck MW, Evanylo GK (1998) Effects of mulches on soil properties and tomato production II. Plant-available nitrogen, organic matter input, and tilth-related properties. J Sustain Agr 13:83–100

Scopa A, Dumontet S (2007) Soil solarization: Effects on soil microbiological parameters. J Plant Nutr 30:537–547

Shearin AF, Reberg-Horton CS, Gallandt ER (2008) Cover crop effects on the activity-density of the weed seed predator *Harpalus rufipes* (Coleoptera: Carabidae). Weed Sci 56:442–450

Shem-Tov S, Fennimore SA (2003) Seasonal changes in annual bluegrass (Poa annua) germinability and emergence. Weed Sci 51:690-695

Shock CC, Jensen LB, Hobson JH, Seddigh M, Shock BM, Saunders LD, Stieber TD (1999) Improving onion yield and market grade by mechanical straw application to irrigation furrows. HortTech 9:251–253

Sideman E (2013) Green manures and cover crops for summer. Maine Organic Farmers and Gardeners Association. http://www.mofga.org/Publications/MaineOrganicFarmerGardener/Summer2013/GreenManures/tabid/2621/Default.aspx. Accessed February 22, 2016

Singh CB, Singh S, Arora VK, Sekhon NK (2015) Residue mulch effects on potato productivity and irrigation and nitrogen economy in a subtropical environment. Potato Research, 58:245–260.

Slovic P (1987) Perception of risk. Science 236:280–285

Smith L (2005). Overseeded annual ryegrass and cereal rye into soybean for winter forage and as a cover crop for weed control and soil conservation. M.S. thesis. Columbia, MO: University of Missouri-Columbia. 53 p

Smith RG (2006) Timing of tillage is an important filter on the assembly of weed communities. Weed Sci 54:705–712

Stoller EW, Wax LM (1973) Periodicity of germination and emergence of some annual weeds. Weed Science 21:574–580

Teasdale JR, Mohler CL (1993) Light transmittance, soil temperature, and soil moisture under residue of hairy vetch and rye. Agron J 85:673–80

Teasdale JR, Mohler CL (2000) The quantitative relationship between weed emergence and the physical properties of mulches. Weed Sci 48:385–392

Terpstra R, Kouwenhoven JK (1981) Inter-row and intra-row weed control with a hoe-ridger. J Agr Eng Res 26:127–134

Tilman EA, Tilman D, Crawley MJ, Johnston AE (1999) Biological weed control via nutrient competition: Potassium limitation of dandelions. Ecolog Applic 9:103–111

Tindall JA, Beverly RB, Radcliffe DE (1991) Mulch effect on soil properties and tomato growth using micro-irrigation. Agron J 83:1028–1034

Torssell B, Eckersten H, Anbari S, Lundkvist A, Verwijst T (2015) Modelling below-ground shoot elongation and emergence time of *Sonchus arvensis* shoots. Acta Agriculturae Scandinavica 65:582–588

Trdan S, Žnidarčič D, Kač M, Vidrih M (2008) Yield of early white cabbage grown under mulch and non-mulch conditions with low populations of onion thrips (*Thrips tabaci* Lindeman). Int J Pest Manage 54:309–318

Van Der Schans D, Bleeker PO, Moledijk L (2006) Practical weed control in arable farming and outdoor vegetable cultivation without chemicals. Lelystad, The Netherlands: Wageningen University

Van Der Weide RY, Bleeker PO, Achten VTJM, Lotz LAP, Fogelberg F, Melander B (2008) Innovation in mechanical weed control in crop rows. Weed Res 48:215–224

Van Toor RF, Till CM, James DE, Teulon DAJ (2004) Evaluation of UV reflective mulches for protection against thrips (*Thrips tabaci*) in onion (*Allium cepa*) crops. NZ Plant Prot 57:209–213

Vanhala P, Kurstjens D, Ascard J, Bertram A, Cloutier DC, Mead A, Raffaelli M, Rasmussen J (2004) Guidelines for physical weed control research: flame weeding, weed harrowing and intra-row cultivation. In: *Proceedings 6th EWRS Workshop on Physical and Cultural Weed Control*, (eds D Cloutier, J Ascard) (8-10 March, Liliehammer, Norway) 194-225. European Weed Research Society

Vavrina CS, Roka FM (2000) Comparison of plastic mulch and bare-ground production economics for short-day onions in a semitropical environment. HortTechnology 10:326–330

Vengris J (1965) Seasonal occurrence of barnyardgrass in potato fields in Massachusetts. Weeds 2:125–134

Walsh MJ, Stratford K, Stone K, Powles SB (2012) Synergistic effects of atrazine and mesotrione on susceptible and resistant wild radish (*Raphanus raphanistrum*) populations and the potential for overcoming resistance to triazine herbicides. Weed Technol 26:341–347

Walters SA, Young BG, Nolte SA (2007) Cover crop and pre-emergence herbicide combinations in no-tillage fresh market cucumber production. J Sustain Agr 30:71–86

Ware GW, McCollum JP (1975) Onions: Producing vegetable crops. Danville, IL: The Interstate Printers & Publishers. Pp 359–377

Warwick SI, Sweet RD (1983) The biology of Canadian weeds. 58. *Galinsoga parviflora* and *G. quadriradiata* (= *G. ciliata*). Can J Plant Sci 63:695–709

Weaver SE (1984). Critical period of weed competition in three vegetable crops in relation to management practices. Weed Res 24:317–325

Weaver SE, McWilliams EL (1980) The biology of Canadian weeds. 44. *Amaranthus retroflexus* L., *A. powellii* S.,Wats. and *A. hybridus* L. Can J Plant Sci 60:1215–1234

Webster TM, Grey TL, Flanders JT, Culpepper AS (2009) Cotton planting date affects the critical period of Benghal dayflower (Commelina benghalensis) control. Weed Sci 57:81–86

Werle R, Bernards ML, Arkebauer TJ, Lindquist JL (2014) Environmental triggers of winter annual weed emergence in the midwestern United States. Weed Sci 62:83–96

Werle R, Sandell LD, Buhler DD, Hartzler RG, Lindquist JL (2014) Predicting emergence of 23 summer annual weed species. Weed Sci 62:267–279

Werner PA, Rioux R (1977) The biology of Canadian weeds. 24. Agropyron repens (L.) Beav. Can J Plant Sci 57:905–919

Weston LA, Duke, S. O. (2003) Weed and crop allelopathy. Crit Rev Plant Sci 22:367–389

White SN, Boyd NS, Van Acker RC (2015) Temperature thresholds and growing-degree-day models for red sorrel (*Rumex acetosella*) ramet sprouting, emergence, and flowering in wild blueberry. Weed Sci 63:254–263

Wickham H (2009) Ggplot2: Elegant graphics for data analysis. New York: Springer-Verlag. 182 p

Wicks GA, Johnston DN, Nuland DS, Kinbacher EJ (1973) Competition between annual weeds and sweet Spanish onions. Weed Sci 21:436–439

Wilcoxon F (1945) Individual comparisons by ranking methods. Biometrics Bull 1:80–83

Wilson RS, Tucker MA, Hooker NH, Lejeune JT, Doohan D, Tucker A, Hooker H (2015) Perceptions and beliefs about weed management: Perspectives of Ohio grain and produce farmers. Weed Technol 22:339–350

Wilson RS, Hooker N, Tucker M, LeJeune J, Doohan D (2009) Targeting the farmer decision making process: A pathway to increased adoption of integrated weed management. Crop Protection. 28:756–764

Zhang J, Weaver SE, Hamill AS (2000) Risks and reliability of using herbicides at below-labeled rates. Weed Technol 14:106–115

Zhang TQ, Tan CS, Warner J (2007). Fresh market sweet corn production with clear and wavelength selective soil mulch films. Can J Plant Sci 87:559–564

Zimdahl RL (2007) Fundamentals of weed science. 3rd edn. Boston: Elsevier/Academic Press. 688 p

Zimmerman CA (1969) The causes and characteristics of weediness in *Portulaca oleracea*. Ph.D. thesis, Ann Arbor, MI: University of Michigan. 263 p

Zwickle S (2011) Weeds and organic weed management: Investigating farmer decisions with a mental models approach. M.S. thesis. Columbus, OH: Ohio State University. 171 p

APPENDIX A. SUPPLEMENTARY MATERIALS.

Table A.1. Assumptions and sources of assumptions used in enterprise budgets of organic onion (*Allium cepa*) and sweet corn (*Zea mays*) production in several weed management systems.

Category	Assumed Value		Distribution and spread of input variables used in risk and sensitivity analyses	Additional Information	Source of Assumption
Farm					
Building footprint	0.05	ha			Estimate
Size of farm	1.42	ha			Average size of organic vegetable farm in Maine, 2014 Organic Survey. https://www.agcensus.usda.gov/Publications/2012/Online_Resources/Organics/
Fuel costs					
Truck	4.3	km L^{-1}			Estimate
Tractor	0.9	km L^{-1}			Estimate
Fuel price	0.9	USD L^{-1}	Normal distribution, standard deviation = 0.18		US Energy Information Administration. US Department of Energy. http://www.eia.gov/petroleum/gasdiesel/
Oil price	1.3	USD L^{-1}			Estimate
Oil use	12.5	% of fuel use			Estimate
Electricity	50	USD $month^{-1}$			Estimate

Table A.1. Continued.

Cell phone	60 USD month^{-1}	Estimate
Annual Fixed Costs		
Depreciation		
Greenhouse(s) - Structure	9,000 USD initial value, 30 year useful life, 75% salvage value	Estimate
Greenhouse(s) - Plastic	1,000 USD initial value, 10 year useful life, 0% salvage value	Estimate
Equipment Storage(s)	15,571 USD initial value, 30 year useful life, 75% salvage value	Estimate
Workshop / Repair Shop / Office	116,785 initial value, 30 year useful life, 75% salvage value	Estimate
Primary Tillage (Plow/Chisel Plow)	13,236 USD initial value, 15 year useful life, 10% salvage value	Estimate
Secondary Tillage (Disc Harrow)	11,679 USD initial value, 15 year useful life, 10% salvage value	Estimate
Fertilizer Spreader	3,893 USD initial value, 15 year useful life, 10% salvage value	Estimate
Transplant Flats	41 USD initial value, 2 year useful life, 20% salvage value	Estimate
Polyethylene Film Applicator	2,000 USD initial value, 15 year useful life, 10% salvage value	Estimate
Dibble Hole Punch Roller	269 USD initial value, 10 year useful life, 0% salvage	Estimate

Table A.1. Continued.

	value				
Irrigation	561 USD initial value, 2 year useful life, 0% salvage value				Estimate
Tools (Small)	500 USD initial value, 15 year useful life, 10% salvage value				Estimate
Computer	779 USD initial value, 5 year useful life, 20% salvage value				Estimate
Tractor(s) Large	38,929 USD initial value, 20 year useful life, 10% salvage value				Estimate
Truck	27,250 USD initial value, 10 year useful life, 10% salvage value				Estimate
Trailer	11,679 USD initial value, 15 year useful life, 10% salvage value				Estimate
Land					
Cultivated Land	4,627	USD ha^{-1}		5% yearly payment	Estimate based on grower survey
Buffer & Rest of Field	2,470	USD ha^{-1}		5% yearly payment	Estimate based on grower survey
Land with Buildings	2,470	USD ha^{-1}		5% yearly payment	Estimate based on grower survey
Insurance					
Crop (Catastrophic)	618	USD ha^{-1}			Estimate based on grower survey
Property	30	USD ha^{-1}			Estimate based on grower survey

Table A.1. Continued.

Tax					
Property	26	USD ha^{-1}		15 USD Mil Rate	Estimate based on grower survey
Onion Assumptions					
Marketable Onions Sold	90	%			Estimate
Wholesale Organic Yellow Dry Onion Price	1.41	USD kg^{-1}	Normal, standard deviation = 0.21		Calculated from seasonal variability in 2016 prices for Boston. USDA Specialty crops terminal markets standard reports https://www.ams.usda.gov /market-news/fruit-and-vegetable-terminal-markets-standard-reports
Main Plot Yield					
Critical Period	40,815	kg ha^{-1}	Normal, standard deviation = 12,911		Field result
Zero Seed Rain	54,914	kg ha^{-1}	Normal, standard deviation = 9,881		Field result
Polyethylene Mulch	47,214	kg ha^{-1}	Normal, standard deviation = 8,013		Field result

Table A.1. Continued.

Hay Mulch	62,244	kg ha^{-1}	Normal, standard deviation = 505	Field result
Labor				
Unskilled labor rate	7.50	USD h^{-1}	Normal distribution, standard deviation = 1.5	2017 minimum wage. Standard deviation based on 20% of minimum wage
Skilled labor rate	15.00	USD h^{-1}		Estimate
Recorded Labor (unskilled)				
Planting - PE Mulch	622.9	h ha^{-1}	Normal distribution, standard deviation = 194.8	Field result
Planting - All others	362.9	h ha^{-1}	Normal distribution, standard deviation = 108.6	Field result
Weeding - Critical Period	1059.1	h ha^{-1}	Normal distribution, standard deviation = 249.2	Field result
Weeding - Zero Seed Rain	1574.4	h ha^{-1}	Normal distribution, standard deviation = 303.3	Field result
Weeding - PE Mulch	1037.4	h ha^{-1}	Normal distribution, standard deviation = 227.4	Field result

Table A.1. Continued.

Weeding - Hay Mulch	762.5	h ha^{-1}	Normal distribution, standard deviation = 92.8	Field result
Mulching - PE Mulch	212.1	h ha^{-1}	Normal distribution, standard deviation = 34.5	Field result
Mulching - Hay Mulch	818.3	h ha^{-1}	Normal distribution, standard deviation = 189.2	Field result
Harvesting - Critical Period	145.5	h ha^{-1}	Normal distribution, standard deviation = 63.2	Field result
Harvesting - Zero Seed Rain	75.3	h ha^{-1}	Normal distribution, standard deviation = 31.8	Field result
Harvesting - PE Mulch	159.9	h ha^{-1}	Normal distribution, standard deviation = 58.5	Field result
Harvesting - Hay Mulch	88.4	h ha^{-1}	Normal distribution, standard deviation = 27.1	Field result

Table A.1. Continued.

Prepare Equipment (skilled)	0.7	h ha^{-1}	Estimate based on field experiment
Primary Tillage (skilled)	1.9	h ha^{-1}	Estimate based on field experiment
Loading Solid Ferilizer Spreader (skilled)	1.2	h ha^{-1}	Estimate based on field experiment
Spread Fertilizer (skilled)	0.1	h ha^{-1}	Estimate based on field experiment
Secondary Tillage (skilled)	1.0	h ha^{-1}	Estimate based on field experiment
Install Drip Irrigation - Tractor (skilled)	3.7	h ha^{-1}	Estimate based on field experiment
Install Drip Irrigation - Manual assistance (unskilled)	3.7	h ha^{-1}	Estimate based on field experiment
Install Drip Irrigation - Connect manifold (unskilled)	4.9	h ha^{-1}	Estimate based on field experiment

Table A.1. Continued.

Drip Irrigation - On/Off (unskilled)	14.5	h ha^{-1}	Estimate based on field experiment
Drip Irrigation - Monitor (unskilled)	43.6	h ha^{-1}	Estimate based on field experiment
Drip Irrigation - Remove (unskilled)	3.2	h ha^{-1}	Estimate based on field experiment
Install Polyethylene Mulch - Tractor (skilled)	3.7	h ha^{-1}	Estimate based on field experiment
Install Polyethylene Mulch - Manual Assistance (unskilled)	3.7	h ha^{-1}	Estimate based on field experiment
Move Transplants to Flatbed Trailer (unskilled)	9.4	h ha^{-1}	Estimate based on field experiment
Harden Off Transplants (unskilled)	37.6	h ha^{-1}	Estimate based on field experiment
Transport Transplants to Field (unskilled)	3.8	h ha^{-1}	Estimate based on field experiment
Move Onions to Cure (unskilled)	51.9	h ha^{-1}	Estimate based on field experiment
Lay Out Onions to Cure (unskilled)	0.6	h Mg^{-1}	Estimate based on field experiment
Remove Onion Tops and Roots (unskilled)	2.5	h Mg^{-1}	Estimate based on field experiment
Move Onions to Vehicle (unskilled)	1.5	h Mg^{-1}	Estimate based on field experiment
Transport Onions to Market (skilled)	8.5	h ha^{-1}	Estimate based on field experiment

Table A.1. Continued.

Order Fertilizer (skilled)	1.0	h $year^{-1}$	Estimate based on field experiment
Order Polyethylene Mulch (skilled)	0.5	h $year^{-1}$	Estimate based on field experiment
Order Hay Mulch (skilled)	1.0	h $year^{-1}$	Estimate based on field experiment
Order Drip Irrigation (skilled)	0.5	h $year^{-1}$	Estimate based on field experiment
Order Seeds (skilled)	0.5	h $year^{-1}$	Estimate based on field experiment
Order Potting Supplies (skilled)	0.5	h $year^{-1}$	Estimate based on field experiment
Pick-up Hay Mulch from Other Farm (unskilled)	3.0	h $year^{-1}$	Estimate based on field experiment
Move Fertilizer In and Out of Storage (unskilled)	0.7	h ha^{-1}	Estimate based on field experiment
Move Polyethylene Mulch In and Out of Storage (unskilled)	0.2	h ha^{-1}	Estimate based on field experiment
Move Drip Irrigation In and Out of Storage (unskilled)	0.2	h ha^{-1}	Estimate based on field experiment
Move Potting Mix / Supplies In and Out of Storage (unskilled)	0.2	h ha^{-1}	Estimate based on field experiment
Equipment Maintenance & Basic Improvements (skilled)	2.5	h ha^{-1}	Estimate based on field experiment

Table A.1. Continued.

Fuel Costs				
Primary Tillage	18.5	L ha^{-1}		Estimate comparable to Lazarus (2015)
Spread Fertilizer (Mechanical)	1.2	L ha^{-1}		Estimate comparable to Lazarus (2015)
Secondary Tillage	2.8	L ha^{-1}		Estimate comparable to Lazarus (2015)
Drip Irrigation Installation	1.2	L ha^{-1}		Estimate comparable to Lazarus (2015)
Polyethylene Mulch Installation	0.9	L ha^{-1}		Estimate comparable to Lazarus (2015)
Harden Off Transplants	4.6	L ha^{-1}		Estimate comparable to Lazarus (2015)
Transport Transplants	4.7	L ha^{-1}		Estimate comparable to Lazarus (2015)
Transport Onion Harvest to Curing	0.9	L ha^{-1}		Estimate comparable to Lazarus (2015)
Other Costs				
Hay Price	0.13	USD kg^{-1}	Triangle Distribution with 0.28, 0.11, and free as high, most-likely, and low values	Maine Hay Directory. University of Maine Cooperative Extension. https://extension.umaine.edu/livestock/hay/

Table A.1. Continued.

Utilities			
Water for Irrigation	0.56	USD m^{-3}	Price of municipal water in Old Town ME. http://www.oldtownwater.org/
Sweet Corn Production			
Wholesale Organic Sweet Corn Price	0.14	USD kg^{-1}	USDA Specialty crops terminal markets standard reports https://www.ams.usda.gov/market-news/fruit-and-vegetable-terminal-markets-standard-reports
Main Plot Yield			
Critical Period	10,500	kg ha^{-1}	Field result
Zero Seed Rain	15,868	kg ha^{-1}	Field result
Polyethylene Mulch	16,407	kg ha^{-1}	Field result
Hay Mulch	17,505	kg ha^{-1}	Field result

Table A.1. Continued.

Labor

Scouting for Disease/Ripeness (skilled)	7.4	USD ha^{-1}	Estimate based on field experiment
Harvesting (unskilled)	49.4	USD ha^{-1}	Estimate based on field experiment
Moving Corn from Field to Truck (unskilled)	9.9	USD ha^{-1}	Estimate based on field experiment
Prepare Equipment (skilled)	0.7	h ha^{-1}	Estimate based on field experiment
Primary Tillage (skilled)	1.9	h ha^{-1}	Estimate based on field experiment
Loading Solid Ferilizer Spreader (skilled)	1.2	h ha^{-1}	Estimate based on field experiment
Spread Fertilizer (skilled)	0.1	h ha^{-1}	Estimate based on field experiment
Secondary Tillage (skilled)	1.0	h ha^{-1}	Estimate based on field experiment
Planting (skilled)	0.4	h ha^{-1}	Estimate based on field experiment
Spring Tine Harrowing (skilled)	0.8	h ha^{-1}	Estimate based on field experiment
Row Cultivation (skilled)	1.0	h ha^{-1}	Estimate based on field experiment
Disc Hilling (skilled)	1.0	h ha^{-1}	Estimate based on field experiment
Harvesting (unskilled)	110.2	h ha^{-1}	Estimate based on field experiment

Table A.1. Continued.

Sorting/Grading (unskilled)	2.5	h ha^{-1}	Estimate based on field experiment
Transporting Off Field (unskilled)	2.5	h ha^{-1}	Estimate based on field experiment
Unloading Harvest (unskilled)	29.7	h ha^{-1}	Estimate based on field experiment
Bagging (unskilled)	27.7	h ha^{-1}	Estimate based on field experiment
Transporting Bags to Vehicle (unskilled)	6.9	h ha^{-1}	Estimate based on field experiment
Transporting Harvest to Market (skilled)	8.5	h ha^{-1}	Estimate based on field experiment
Order Fertilizer (skilled)	2.5	h ha^{-1}	Estimate based on field experiment
Order Seeds (skilled)	1.2	h ha^{-1}	Estimate based on field experiment
Move Fertilizer from Delivery to Storage (unskilled)	0.7	h ha^{-1}	Estimate based on field experiment
Equipment Maintenance & Basic Improvements (skilled)	2.5	h ha^{-1}	Estimate based on field experiment
Fuel Costs			
Primary Tillage	18.5	L ha^{-1}	Estimate comparable to Lazarus (2015)
Spread Fertilizer (Mechanical)	1.2	L ha^{-1}	Estimate comparable to Lazarus (2015)

Table A.1. Continued.

Secondary Tillage	2.8	L ha^{-1}	Estimate comparable to Lazarus (2015)
Planting	4.7	L ha^{-1}	Estimate comparable to Lazarus (2015)
Spring Tine Harrowing	1.6	L ha^{-1}	Estimate comparable to Lazarus (2015)
Row Cultivation	4.8	L ha^{-1}	Estimate comparable to Lazarus (2015)
Disc Hilling	4.8	L ha^{-1}	Estimate comparable to Lazarus (2015)
Transport Harvest Off Field	55.1	L ha^{-1}	Estimate comparable to Lazarus (2015)
Annual Fixed Costs			
Spring Tine Harrow	3,000 USD, 15 year useful life, 10% salvage value		Estimate
Cultivator & Disc Hiller (4-row combined)	7,000 USD, 15 year useful life, 10% salvage value		Estimate

Table A.2. Enterprise budget summary for organic onion (*Allium cepa*) production using four different weed management systems. Each system was implemented in realistic (main plots) as well as weed-free (weed-free subplots) conditions.

	Main Plots			
	Critical Period	Zero Seed Rain	PE Mulch	Hay Mulch
	USD ha^{-1}			
Annual Revenue	52,243	70,291	60,434	72,442
Annual Operating Expenses				
Labor	15,411	19,373	17,760	19,946
Fertilizer				
Soybean Meal	2,779	2,779	2,779	2,779
Composted Poultry Litter	1,866	1,866	1,866	1,866
Bone Char	863	863	863	863
Fish Hydrolysate	3,335	3,335	3,335	3,335
Onion Seed	2,257	2,257	2,257	2,257
Seedling Mix (Potting Soil)	2,897	2,897	2,897	2,897
Mulch				
Black Plastic	0	0	509	0
Hay	0	0	0	3,850
Diesel Fuel	58	58	59	90
Oil	11	11	11	17
Utilities				
Electricity	726	726	726	726
Water	56	63	34	49
Total Operating Expenses	30,259	34,229	33,097	38,677
Total Overhead Expenses	86	86	86	86
Annual Ownership Expenses				
Depreciation and Interest				
Buildings & Structures	902	902	902	902
Tillage & Cultivation Equipment	1,055	1,055	1,055	1,055
Fertilization Equipment	165	165	165	165
Transplanting Equipment	254	254	254	254
Black Plastic Equipment	0	0	85	0
Irrigation	4,076	4,076	4,076	4,076
Tools	109	109	109	109
Tractors	1,236	1,236	1,236	1,236
Trucks	1,731	1,731	1,731	1,731

Table A.2. Continued.

Trailers	495	495	495	495
Land	477	477	477	477
Insurance	1,123	1,123	1,123	1,123
Taxes	46	46	46	46
Total Ownership Expenses	11,668	11,668	11,752	11,668
Total Annual Cost	42,013	45,983	44,936	50,431
Return over Variable Cost (ROVC)	21,984	36,061	27,337	33,765
Net Farm Income (NFI)	10,230	24,308	15,498	22,011

Table A.3. Enterprise budget summary for organic sweet corn (*Zea mays*) production using four different weed management systems.

	Prior Year Weed Management System			
	Critical Period	Zero Seed Rain	PE Mulch	Hay Mulch
	USD ha^{-1}			
Annual Revenue	9,126	11,428	11,719	11,921
Annual Operating Expenses				
Labor	1,448	1,424	1,526	1,510
Fertilizer				
Soybean Meal	2,149	2,149	2,149	2,149
Composted Poultry Litter	1,416	1,416	1,416	1,416
Bone Char	254	254	254	254
Fish Hydrolysate	654	654	654	654
Corn Seed	840	840	840	840
Diesel Fuel	75	75	75	75
Oil	9	9	9	9
Utilities				
Electricity	726	726	726	726
Total Operating Expenses	7,571	7,547	7,650	7,633
Total Overhead Expenses	86	86	86	86
Annual Ownership Expenses				
Depreciation and Interest				
Buildings & Structures	221	221	221	221
Tillage & Cultivation Equipment	723	723	723	723
Fertilization Equipment	47	47	47	47
Tools	34	34	34	34
Tractors	352	352	352	352
Trucks	492	492	492	492
Trailers	141	141	141	141
Land	477	477	477	477
Insurance	1,123	1,123	1,123	1,123
Taxes	46	46	46	46
Total Ownership Expenses	3,656	3,656	3,656	3,656
Total Annual Cost	11,314	11,290	11,392	11,376
Return over Variable Cost (ROVC)	1,555	3,881	4,069	4,288
Net Farm Income (NFI)	-2,187	138	326	545

Figure A.1. Approval from the Institutional Review Board (IRB) to work with human subjects.

(KEEP THIS PAGE AS ONE PAGE – DO NOT CHANGE MARGINS/FONTS!!!!!!!!!)

APPLICATION FOR APPROVAL OF RESEARCH WITH HUMAN SUBJECTS
Protection of Human Subjects Review Board, 114 Alumni Hall, 581-1498

PRINCIPAL INVESTIGATOR: Bryan Brown
EMAIL: bryan.brown@maine.edu TELEPHONE: 207-240-2921
CO-INVESTIGATOR(S): NA
FACULTY SPONSOR (Required if PI is a student): Eric Gallandt
TITLE OF PROJECT: Balancing economy and ecology: A systems comparison of leading organic weed management strategies

START DATE: 2/18/15 PI DEPARTMENT: School of Food and Agriculture
MAILING ADDRESS: 5722 Deering Hall
FUNDING AGENCY (if any): Northeast Sustainable Agriculture Research and Education
STATUS OF PI:
FACULTY/STAFF/GRADUATE/UNDERGRADUATE Graduate

1. If PI is a student, is this research to be performed:

- ☐ **for an honors thesis/senior thesis/capstone?**
- ☒ **for a doctoral dissertation?**
- ☐ **other (specify)**
- ☐ **for a master's thesis?**
- ☐ **for a course project?**

2. Does this application modify a previously approved project? no (Y/N). If yes, please give assigned number (if known) of previously approved project:

3. Is an expedited review requested? yes (Y/N).

SIGNATURES: All procedures performed under the project will be conducted by individuals qualified and legally entitled to do so. No deviation from the approved protocol will be undertaken without prior approval of the IRB.

Faculty Sponsors are responsible for oversight of research conducted by their students. By signing this application page, the Faculty Sponsor ensures that he/she has read the application and that the conduct of such research will be in accordance with the University of Maine's *Policies and Procedures for the Protection of Human Subjects of Research.*

1/15/15 Bryan Brown Eric Gallandt
Date **Principal Investigator** **Faculty Sponsor**

Co-Investigator **Co-Investigator**

****

FOR IRB USE ONLY Application # 2015-01-08 Date received 1/20/15 Review (F/E): E
Expedited Category: ______

ACTION TAKEN:

- ✓ **Judged Exempt; category 2. Modifications required? Y (Y/N) Accepted (date) 1/30/15**
- ____ **Approved as submitted. Date of next review: by __________. Degree of Risk: ________**
- ____ **Approved pending modifications. Date of next review: by __________. Degree of Risk: ________**
  Modifications accepted (date): __________.
- ____ **Not approved. (See attached statement.)**
- ____ **Judged not research with human subjects**

Date: 1/26/15 Chair's Signature: Cynthia A. Erdley **12/2012**

Table A.4. Interview questions asked to each case study farmer.

Interview questions
What does a typical crop rotation look like for you?
On average, how many times do you weed your onions? Your winter squash? Your cabbage?
How much of your weeding is done by hand?
How much weeding do you do compared to other organic farmers? Has that changed over time as a result of the weeds or your philosophy?
What factors caused you to practice your strategy?
Now that you've done it for a while, what are some of the short- and long-term benefits of your strategy?
Due to your strategy, do you think you use more or less water, fertilizer, or soil amendments?
What types of weeds flourish in your strategy?
How tall do you feel weeds have to get before they do significant damage?
If you had an extremely high or extremely low weed seedbank would you still use your strategy?
If your soil quality was much better or much worse would you still use your strategy?
What are the drawbacks of your strategy compared to the other strategies?
What kinds of specialized equipment have helped you implement your strategy?
Do you irrigate your crops with spray or drip?
How does wet weather affect your farm operations? Can you still weed?
How does drought affect your farm operations?

Table A.4. Continued.

In order to determine the importance of various criteria involved in the decision of which strategy to follow, I would like you to rank the following pairs of terms on a scale from zero to ten, with zero meaning that the first term is extremely important and the second term not at all important, visa versa for ten, and five meaning that the two terms are equally important:
Having a small amount of weeding labor or having good soil quality
Having a small amount of weeding labor or being environmental sustainable
Having a small amount of weeding labor or having a small weed seedbank
Being environmental sustainable or having good soil quality
Being environmentally sustainable or having a small weed seedbank
Having good soil quality or having a small weed seedbank

Table A.5. Schedule of field operations for experiments conducted in 2016 comparing efficacy of intra-row cultivation tools using white mustard and white proso millet as surrogate weeds.

Experiment	Field	Operation	Date
Screening	E	Primary tillage	28 Apr
		Secondary tillage	10 May
		Maize planted	11 May
		Spring tine harrowing	13 May
		Spring tine harrowing	17 May
		Mustard and millet planted	25 May
		Cultivation treatments	2 Jun
	Q	Primary tillage	9 May
		Secondary tillage	17 May
		Maize planted	18 May
		Spring tine harrowing	20 May
		Spring tine harrowing	31 May
		Mustard and millet planted	31 May
		Cultivation treatments	10 Jun
Forward speed	E	Primary tillage	6 Jun
		Secondary tillage	8 Jun
		Maize planted	9 Jun
		Spring tine harrowing	14 Jun
		Millet planted	21 Jun
		Mustard planted	24 Jun
		Cultivation treatments	1 Jul
	Q	Secondary tillage	5 Jul
		Maize planted	5 Jul
		Millet planted	14 Jul
		Mustard planted	18 Jul
		Cultivation treatments	25 Jul
Soil moisture	E	Secondary tillage	20 Jul
		Maize planted	21 Jul
		Millet planted	25 Jul
		Mustard planted	28 Jul
		Cultivation treatments	2 Aug
	Q	Secondary tillage	1 Aug
		Maize planted	2 Aug

Table A.5. Continued.

		Millet planted	8 Aug
		Mustard planted	10 Aug
		Cultivation treatments	16 Aug
Weed size	E	Secondary tillage	4 Aug
		Maize planted	5 Aug
		Millet first cohort planted	8 Aug
		Mustard first cohort planted	10 Aug
		Millet second cohort planted	12 Aug
		Mustard second cohort planted	14 Aug
		Millet third cohort planted	17 Aug
		Mustard third cohort planted	18 Aug
		Cultivation treatments	25 Aug
	Q	Secondary tillage	22 Aug
		Maize planted	22 Aug
		Millet first cohort planted	24 Aug
		Mustard first cohort planted	26 Aug
		Millet second cohort planted	29 Aug
		Mustard second cohort planted	31 Aug
		Millet third cohort planted	4 Sep
		Mustard third cohort planted	6 Sep
		Cultivation treatments	13 Sep

BIOGRAPHY OF THE AUTHOR

Bryan Brown was born in Bangor, Maine on May 15, 1987. He attended Bangor High School, where he pursued interests in science and art, and captained the tennis team before graduating in 2005. He attended Colby College in Waterville, ME and graduated in 2009 with a Bachelor of Arts in Biology and a minor in Environmental Studies. After college Bryan pursued a mix of biology and agriculture jobs. In the summer of 2013 he began graduate school, finding the perfect balance between biology and agriculture in the Ecology and Environmental Sciences program at the University of Maine, with advisor Dr. Eric Gallandt, Professor of Weed Ecology and Management. After receiving his degree, Bryan will be joining the New York State Integrated Pest Management Program, as an Alternative Weed Management Specialist. Bryan is a candidate for the Doctor of Philosophy degree in Ecology and Environmental Sciences from the University of Maine in May 2017.